NASA
SPACE VEHICLE
DESIGN CRITERIA
(CHEMICAL PROPULSION)

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LIQUID ROCKET ENGINE INJECTORS

MARCH 1976

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, part of the series on Chemical Propulsion, is one such monograph. A list of all monographs issued prior to this one can be found on the final pages of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that these documents, revised as experience may indicate to be desirable, eventually will provide uniform design practices for NASA space vehicles.

This monograph, "Liquid Rocket Engine Injectors", was prepared under the direction of Howard W. Douglass, Chief, Design Criteria Office, Lewis Research Center; project management was by Harold Schmidt and M. Murray Bailey. This monograph was written by G. S. Gill* and W. H. Nurick, Rocketdyne Division, Rockwell International Corporation and was edited by Russell B. Keller, Jr. of Lewis. To assure technical accuracy of this document, scientists and engineers throughout the technical community participated in interviews, consultations, and critical review of the text. In particular, Robert G. Carroll of Pratt & Whitney Aircraft Division, United Technologies Corporation; David A. Fairchild of Aerojet Liquid Rocket Company; and Larry H. Gordon of the Lewis Research Center reviewed the monograph in detail.

Comments concerning the technical content of this monograph will be welcomed by the National Aeronautics and Space Administration, Lewis Research Center (Design Criteria Office), Cleveland, Ohio 44135.

March 1976

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*Currently with Societe d'Etude de la Propulsion Par Reaction, France.

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GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in design, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into two major sections that are preceded by a brief introduction and complemented by a set of references.

The State of the Art, section 2, reviews and discusses the total design problem, and identifies <u>which</u> design elements are involved in successful design. It describes succinctly the current technology pertaining to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Design Criteria* and Recommended Practices.

The *Design Criteria,* shown in italics in section 3, state clearly and briefly <u>what</u> rule, guide, limitation, or standard must be imposed on each essential design element to assure successful design. The *Design Criteria* can serve effectively as a checklist of rules for the project manager to use in guiding a design or in assessing its adequacy.

The Recommended Practices, also in section 3, state <u>how</u> to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The Recommended Practices, in conjunction with the *Design Criteria,* provide positive guidance to the practicing designer on how to achieve successful design.

Both sections have been organized into decimally numbered subsections so that the subjects within similarly numbered subsections correspond from section to section. The format for the Contents displays this continuity of subject in such a way that a particular aspect of design can be followed through both sections as a discrete subject.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the designer.

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LIQUID ROCKET ENGINE INJECTORS

1. INTRODUCTION

The injector in a liquid rocket engine atomizes and mixes the fuel with the oxidizer to produce efficient and stable combustion that will provide the required thrust without endangering hardware durability. Injectors usually take the form of a perforated disk at the head of the rocket engine combustion chamber, and have varied from a few inches to more than a yard in diameter. This monograph treats specifically bipropellant injectors, emphasis being placed on the liquid/liquid and liquid/gas injectors that have been developed for and used in flight-proven engines. The information provided has limited application to monopropellant injectors and gas/gas propellant systems.

In the past, the design of injectors has been primarily an art that depended for success on the experience and intuition of the injector design team. This design approach led to expensive, time-consuming development programs and often to marginal final designs. More recently, injector design capability has been improved considerably by the use of computer programs that characterize the combustion field and by cold-flow techniques that are used to determine the mass, mixture-ratio, and dropsize distribution characteristics. In addition, a long history of practical experience has pinpointed numerous problem areas in injector design and operation. The purpose of this monograph is to point out critical problems that may arise during injector development and to indicate the approaches that lead to successful design.

The monograph has been organized to provide a systematic guide for the working designer. The first and foremost step in injector design is to establish the injector flow-system geometry. This system geometry is the flow-controlling aspect of the injector, and is composed of the total injector element pattern, the individual orifice geometry used in the total pattern, and the flow-system geometry or manifolding upstream of the orifices. The second step is to develop the injector assembly; this step involves handling the structural and material aspects of the proposed injector and includes the design of the auxiliary components. These steps, accomplished systematically with careful attention to detail, result in a successful rocket engine injector.

2. STATE OF THE ART

A wide variety of injectors has been employed in operational space vehicles. A summary of the chief design features of representative production injectors is presented in table I*. The discussion of injectors herein is applicable not only to the injectors listed but also to many small-motor, gas-generator, and large-scale concepts not listed. In engines that have been developed and flown to date, the injector flowrate has varied by a factor of more than one hundred thousand, propellant density by a factor of more than one hundred, and chamber pressure by a factor of more than fifteen. Both storable and cryogenic** propellants have been used; some were corrosive, some highly toxic, some thermally unstable. Some injectors have operated for many minutes, some have been pulsed for very short durations (milliseconds), and a few have been deeply throttled. Designs have included ring-type faces, "solid" faces, and porous faces. The requirement that had to be satisfied by each injector, regardless of operating conditions, was the attainment of required performance without endangering combustion stability or the durability of the injector, chamber wall, and baffles.

Injector performance has increased steadily since the early days of rocket engine injector development. The increase has been accomplished mainly through improved analytical models that led to more sophisticated injector designs. Durability has been upgraded through improved film- or barrier-cooling effectiveness, more uniform injectant distribution, and improved fabrication techniques and materials. Stability has been improved through a better understanding of the combustion process and through the use of stabilization devices such as baffles and acoustic absorbers.

As noted earlier, however, the key to successful injector design lies in careful attention to detail, first in the design of the injector flow system and then in the development of the injector assembly. These two basic steps are treated in depth in the sections that follow.

2.1 INJECTOR FLOW-SYSTEM GEOMETRY

The objective of the injector designer is to specify an injector design that will produce high combustion performance and stable operation without affecting injector and thrust chamber durability. This formidable task can be accomplished only through proper selection and design specification of the entire injector flow-system geometry, which includes (1) total element pattern, (2) individual orifice geometry, and (3) flow system (manifolding) upstream of the orifices. Figure 1 illustrates the relationship of the various injector components to the total injector flow-system geometry.

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*Factors for converting U.S. customary units to the International System of Units (SI units) are given in Appendix A.

**Terms and symbols, materials, and abbreviations are defined or identified in Appendix B.

Table I. – Chief Design Features of Injectors

Vehicle, Engine	Propellants	Performance* (η_c), %	Thrust, lbf	Chamber pressure, psi	Injector diameter, in.	Element type	Number primary elements
Redstone, A-7	LOX/Alcohol	——	78 000	315	21.7	Like doublet	355 (o) 355 (f)
Jupiter	LOX/RP-1	94.7	150 000	530	20.9	Like doublet	361 (o) 361 (f)
Thor, MB-3	LOX/RP-1	95.5	170 000 SL	588	20.9	Like doublet & triplet	335 (o) 582 (f)
Atlas, MA-5 booster (2 TCA/engine)	LOX/RP-1	95.5	165 000 (each TCA) SL	577	20.9	Like doublet & triplet	335 (o) 582 (f) (each TCA)
Atlas, MA-5 sustainer	LOX/RP-1	96.4	57 000 SL	706	12.4	Like triplet	144 (o) 175 (f)
Titan I, booster (2 TCA/engine)	LOX/RP-1	97.8	180 000 (each TCA) SL	637	21.6	Like doublet	560 (o) 610 (f) (each TCA)
Titan I, stage 2	LOX/RP-1	98.9	80 000 Vac	682	14.2	Like doublet	328 (o) 392 (f)
Saturn IB, H-1	LOX/RP-1	97.3	204 300 SL	705	20.9	Like doublet & triplet	365 (o) 612 (f)
Saturn IC, F-1	LOX/RP-1	93.8	1 522 000 SL	1128	39.2	Like doublet	714 (o) 702 (f)
Agena, LR81-BA-11	IRFNA/UDMH	95.7 (shifting)	15 800 Vac	506	10.8	Triplet	88 (o) 176 (f)
Lance (XRL), booster	IRFNA/UDMH	93.4 (shifting)	42 000 SL	950	Annular 12.5 OD	Unlike doublet	460

*Frozen equilibrium unless specified otherwise.

Used in Major Operational Vehicles

Pattern	Primary orifice diameter, in.		Inlet manifolding		Body material	Face material	Face type	Combustion stabilization devices
	O	F	O	F				
Radial fan/ Concentric ring	0.113	0.1015	Dome 1 inlet	Annular ring	4130 steel	4130 steel	Concentric ring (brazed)	None
Radial fan/ Concentric ring	.113	.089	Dome 1 inlet	Annular ring	4130 steel	4130 steel	Concentric ring (brazed)	None
Radial fan/ Concentric ring	.113	.0635	Dome 1 inlet	Annular ring	347 CRES	OFHC copper	Concentric ring (brazed)	Copper baffles 7 compartments
Radial fan/ Concentric ring	.113	.0635	Dome 1 inlet	Annular ring	347 CRES	OFHC copper	Concentric ring (brazed)	Copper baffles 7 compartments
Radial fan/ Concentric ring	.120	.0935	Dome 1 inlet	Annular ring	4130 steel	4130 steel	Concentric ring (brazed)	None
Radial fan/ Concentric ring	.119	—	Dome	Annular ring	347 CRES	347 CRES	Concentric ring (welded)	None
Radial fan/ Concentric ring	.085	.057	Dome	Annular ring	347 CRES	347 CRES	Concentric ring (welded)	None
Radial fan/ Concentric ring	.120	.082	Dome 1 inlet	Annular ring	347 CRES	OFHC copper	Concentric ring (brazed)	Copper baffles 7 compartments
Radial fan/ Concentric ring	.242	.281	Annular dome 2 inlets	Annular ring	347 CRES	OFHC copper	Concentric ring (brazed)	Copper baffles 13 compartments
Grid/ Alternating fan	.111	.049	Annular ring	Dome Valve in head	6061 aluminum	6061 aluminum	Continuous face	None
Tang. fan/ Concentric ring	.073	.0515	4 Annular segments – 1 inlet	4 Radials – 1 inlet	Tens-50 aluminum	Tens-50 aluminum	Continuous face, 5 ring	Ablative baffles and acoustic absorbers

(continued)

Table I. – Chief Design Features of Injectors

Vehicle, Engine	Propellants	Performance* (η_c), %	Thrust, lbf	Chamber pressure, psi	Injector diameter, in.	Element type	Number primary elements
Lance (XRL), sustainer	IRFNA/UDMH	91.8 (shifting)	4000	930	5.0	Unlike doublet (pintle)	108
Titan II, booster (2 TCA/engine)	N_2O_4/A-50	97.2	215 000 (each TCA) SL	785	21.8	Like doublet	568 (o) 516 (f) (each TCA)
Titan II, stage 2	N_2O_4/A-50	97.4	100 000 Vac	827	14.5	Quadlet	1319 (o) 818 (f)
Transtage, AJ10-138	N_2O_4/A-50	96.1 (shifting)	8150 Vac	108	11.9	Unlike triplet & quadlet	336
Titan III, booster (2 TCA/engine)	N_2O_4/A-50	98.0	220 000 (each TCA)	817	21.65	Quadlet	504 (each TCA)
Apollo SPS	N_2O_4/A-50	97.5	21 500 Vac	100	17.6	Unlike doublet	575
Apollo, lunar descent	N_2O_4/A-50	96.2 (shifting)	9850 Vac	104	13.2	Coaxial pintle	36 (o) 1 (f sheet)
Apollo, lunar ascent	N_2O_4/A-50	97.1 (shifting)	3500 Vac	120	7.8	Unlike doublet	177
Saturn II and IV B, J-2	LOX/H_2	98.6	230 000 Vac	780	18.5	Coaxial	614
Centaur, RL10A-3	LOX/H_2	98.5 (shifting)	15 000 Vac	400	10.3	Coaxial	216
SSME**	LOX/H_2	99.6 (shifting)	509 000 Vac	3250	17.8	Coaxial	600

*Frozen equilibrium unless specified otherwise.

**Not operational, but advanced development.

Used in Major Operational Vehicles (concluded)

Pattern	Primary orifice diameter, in.		Inlet manifolding		Body material	Face material	Face type	Combustion stabilization devices
	O	F	O	F				
Tang fan/ Concentric ring	0.060 X var depth	0.060 X var depth	Annular ring – 2 inlets	Radial 1 inlet	Tens-50 aluminum	347 CRES	—	Acoustic absorbers
Radial fan/ Concentric ring	0.119	0.082	Dome – offset inlet	Annular ring	347 CRES	347 CRES	Concentric ring (welded)	None
Quadlet/ Concentric ring	.049	.037	Dome – offset inlet	Annular ring	347 CRES	347 CRES	Concentric ring (welded)	6 baffles + hub
Radial/ O-F Fan O-Showerhead	.036 & .051	.029	Dome – 2 offset inlets	Dome – 1 offset inlet	6061 aluminum	6061 aluminum	Concentric ring (welded)	Baffles
Quadlet/ Concentric ring	.1065	.0689	Dome – offset inlet	Annular ring	347 CRES	—	Concentric ring (welded)	7 radial baffles
Tang fan/ Concentric ring	.041 - .073	.041 - .077	2 domes/ annular rings	Central dome	5083 aluminum	5083 aluminum	Concentric ring (welded)	5 baffles + hub
Radial (o) Axial (f)	Variable		Dome – 1 inlet	Annular ring	Titanium	Titanium and columbium	Movable sleeve	None
Tang fan/ Concentric ring	.0504 & .0362	.0397 & .0319	Dome – 1 offset inlet	Dome – 1 offset inlet	2219 aluminum	2219 aluminum	Concentric ring (E B weld)	Aluminum baffle 3 compartments and acoustic absorbers
Concentric ring	.182	.049 annulus	Annular dome – 1 inlet	Annular ring	Inconel 718	347 CRES Rigimesh	Porous face (welded)	Tuned elements
Concentric ring	.079	.017 annulus	Dome – 1 inlet	Annular ring	347 CRES	347 CRES Rigimesh	Porous face (welded)	None
Concentric ring	.188	.065 annulus	Annular dome – 1 inlet	Annular ring	Inconel 718	347 CRES Rigimesh	Porous face (welded)	Baffles

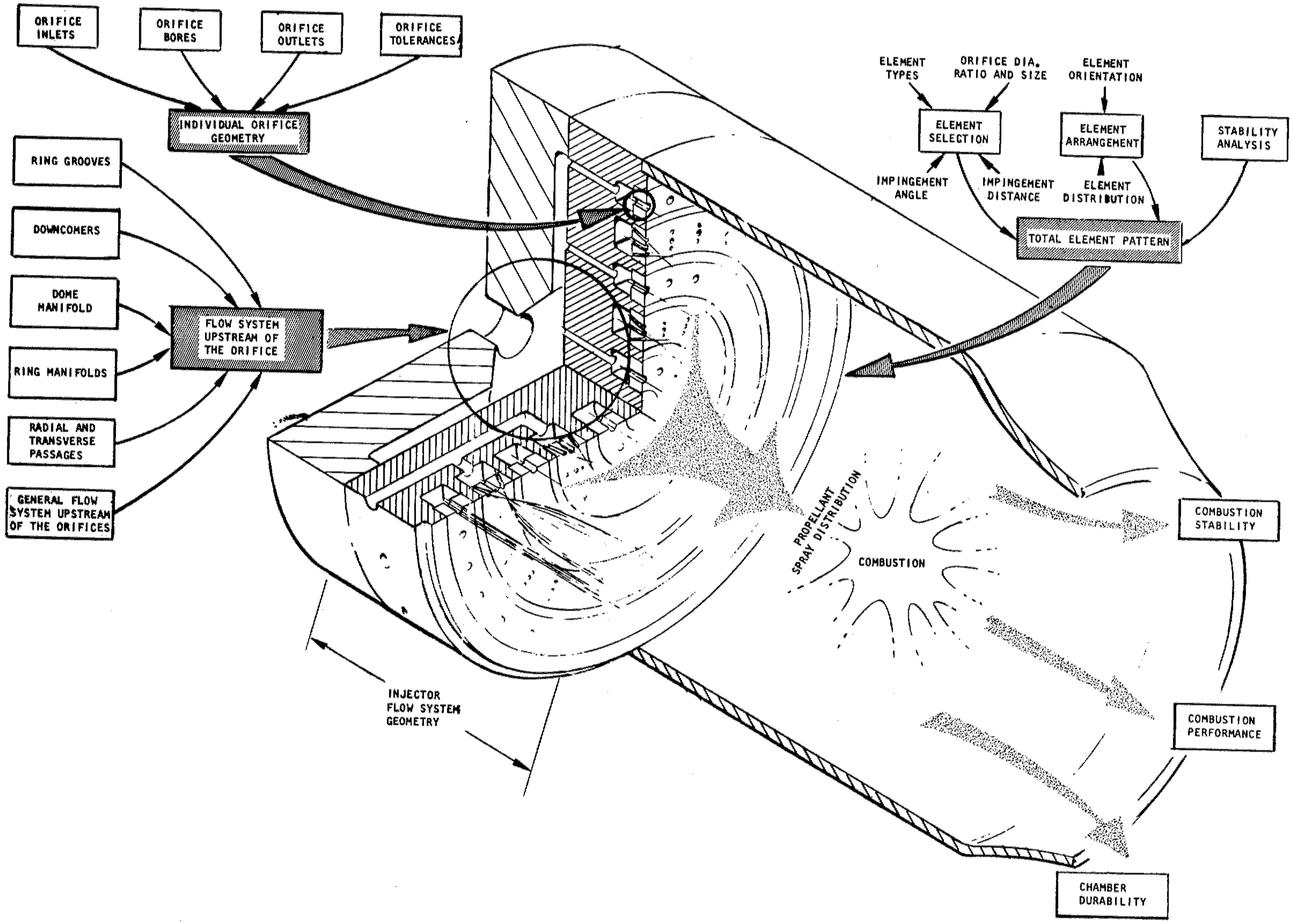


Figure 1. – Relation of injector components to total injector flow system.

Design of the entire flow-system geometry specifies the spray distributions (i.e., mass, mixture-ratio, and dropsize distributions) and baffle arrangement if needed. Often in the past, design of an injector flow system has been a relatively rudimentary process and frequently has resulted in numerous problems. Techniques now available, even though inadequate in some respects, produce a much improved initial design of the injector flow system.

2.1.1 Total Element Pattern

Design of the total element pattern consists of (1) selection of the injection element, including the type and designation of all geometric parameters, (2) arrangement of the elements, including the orientation of an element with respect to the chamber wall and to other elements as well as element distribution across the injector face, and (3) provision for stabilization devices, such as baffles, acoustic absorbers, and feed-system resistors, that are integral parts of the injector. Proper design of the total pattern ensures that the propellants will mix in the desired manner and result in high performance, stable operation, and chamber and injector durability.

The mixing and propellant dropsize levels that must be achieved within the combustor generally are specified through the use of combustion models. The most comprehensive models available are those developed by the JANNAF Performance Standardization Working Group and described in references 1 and 2. These combustion-model programs, in addition to experimental evidence, have shown that the level of combustion performance is a strong function of the propellant spray distributions (mass, mixture-ratio, and drop size). High combustion efficiency requires a reasonably uniform overall mixture-ratio distribution, initial drop size consistent with the chamber geometry and operating conditions, and a uniform mass distribution. Low performance results from a poor mixture-ratio distribution or incomplete vaporization. Propellant mixing and atomization are controlled by the total element pattern of the injector.

Hardware durability is affected strongly by local mixture-ratio and mass distribution near the injector face or chamber walls and also by the radial and transverse winds* produced by overall mass or mixture-ratio maldistribution. Impingement of highly reactive propellant on the chamber wall can cause catastrophic failure of the chamber as a result of a high rate of chemical reaction or erosion of material. Although high combustion rates are attractive from a performance standpoint, they can produce high heat-transfer rates and damage the chamber. The mixture-ratio and mass distributions of propellant near the chamber walls are controlled by the injector element and its location and orientation on the injector face.

Combustion stability has been found to be sensitive to changes in local mixture-ratio and mass distribution. Changes in only those elements at the baffle-baffle junction or the

*Flow of gases from regions of high pressure to regions of low pressure.

wall-baffle junction have significantly changed the stability characteristics. Nonuniform distributions designed to tailor the amount of propellants within the sensitive region of a particular acoustic mode have been successful in producing stable combustion.

2.1.1.1 ELEMENT SELECTION

The choice of the element or elements depends on the application. Tables II and III present comparisions of injector elements that have been used in production engines or have been extensively studied. Note that some of the elements can be designed for wall compatibility*, whereas others provide high performance. Note also that considerably more information is available for liquid/liquid injection (table II) than for gas/liquid injection (table III).

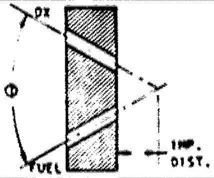
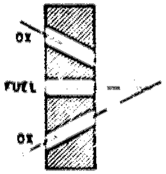
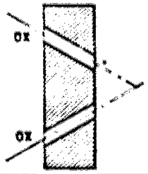
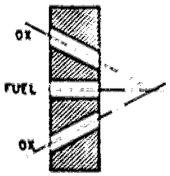
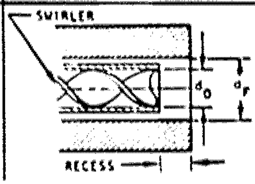
Parameters that influence element selection are as follows:

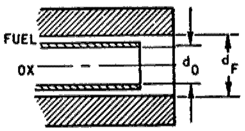
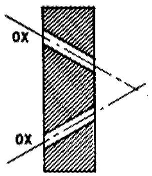
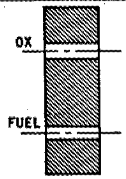
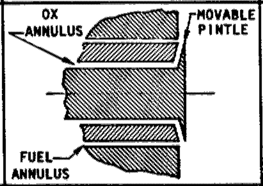
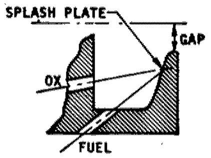
- Propellants: hypergolic, cryogenic, storable.
- Condition of propellants: liquid, gas, gel.
- Chamber walls: uncooled, ablative, regeneratively cooled.
- Chamber length: limiting process (mixing or vaporization).
- Operating conditions: mixture ratio, chamber pressure.
- Throttling requirements.
- System-pressure-drop limitation.
- Engine life: restarts, total duration.

All of the above parameters directly or indirectly affect combustion performance, heat transfer, chamber materials compatibility, or stability. (Some affect more than one.) Each imposes specific demands on the element (e.g., local mixture-ratio and mass gradients or spray drop size). Consideration of the advantages and disadvantages listed in tables II and III suggests that no single element type or design can accomplish everything. (Note that this table does not exhaust element types that have been conceived. Elements listed are restricted to those that have been utilized in production engines or otherwise studied extensively.) If a single element type is selected for the entire injector, then large compromises generally are required. However, when a combination of element types or specific element-type design variations or orientations can be used, then generally the performance, heat-transfer, or stability specifications can be met without compromise.

*Mass and mixture-ratio distribution produced by element does not endanger wall durability or integrity.

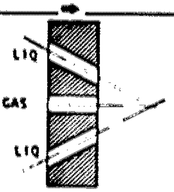
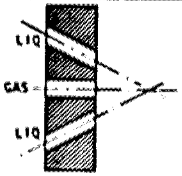
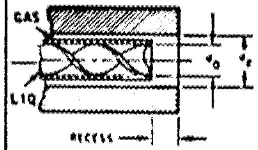
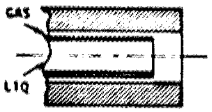
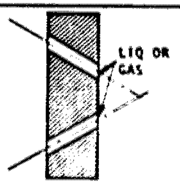
Table II. – Comparison of Typical Injector Elements for Liquid/Liquid Injection

ELEMENT DESIGNATION	ELEMENT CONFIGURATION (FLOW DIRECTION) ➡	ADVANTAGES	DISADVANTAGES	DESIGN CORRELATIONS*	ENGINE APPLICATION
UNLIKE DOUBLET (1 ON 1) ● ○		Proven dependability Good overall mixing Simple to manifold Extensively studied	Subject to blowapart with hypergolic propellants Wall compatibility problems due to mixture-ratio gradients Sensitive to design tolerances Performance sensitive to continuous throttling	Mixing (ref. 3) Atomization (ref. 4) <u>Noncircular orifice geometry</u> (rectangular and triangular) Mixing (ref. 5) Atomization (ref. 5)	LEM ascent engine Delta launch vehicle
UNLIKE TRIPLET (2 ON 1) ● ○ ●		Good overall mixing Resultant spray direction is axial Proven dependability	Subject to blowapart with hypergolic propellants Wall compatibility is good only when fuel is used in outer orifices Sensitive to design tolerances Performance sensitive to continuous throttling	Mixing (ref. 6) Atomization (ref. 7)	Agena upper stage, Gemini/Agena target vehicles
UNLIKE QUADLET (2 ON 2) ○● ○● (a) ●○ ○● (b)		Can be used near chamber wall Resultant spray direction is axial Proven dependability	Subject to blowapart with hypergolic propellants Difficult to manifold Not well characterized	Mixing (ref. 6)	Titan III first stage, Titan II and III second stage, Gemini LV second stage (a) Spacecraft propulsion engines (b)
UNLIKE PENTAD (4 ON 1) ● ●○● ●		Good overall mixing High performance Applicable to very high or very low mixture ratios or density ratios Well characterized	Subject to blowapart with hypergolic propellants Difficult to manifold Wall compatibility problems Performance sensitive to throttling Tends to produce high heat flux to injector face	Mixing (ref. 6) Atomization (ref. 8)	None known
CONCENTRIC TUBE (WITH SWIRLER)		Good mixing and atomization Low pressure drop Proven dependability	Difficult to fabricate if annulus gap is very small (≲0.06 in.) Tends to become unstable when throttled	None	Russians use this element extensively Candidate Surveyor vernier (MIRA 150A)

CONCENTRIC TUBE (WITHOUT SWIRLER)		Very good wall compatibility Low pressure drop	Poor mixing Difficult to fabricate if annulus gap is very small (<0.06 in.) Tends to become unstable when throttled	None	Russians use this element extensively Candidate Surveyor vernier (MIRA 150A)
LIKE DOUBLET (1 ON 1) ● OR ○ ● ○		Easy to manifold Excellent for deliberate control of spray for wall compatibility Good mixing Very stable element Not subject to blowapart Well understood Proven dependability	Requires increased axial distance to mix fuel and oxidizer Sensitive to design tolerances	Mixing (ref. 8) Atomization (ref. 4)	Gemini LV first stage; Titan I and II first stage Redstone, Jupiter, Thor, Atlas boosters H-1, F-1 engines Upper stage VEGA
SHOWERHEAD ● ○		Excellent for boundary layer cooling Excellent for wall compatibility Easy to manifold Not subject to blowapart Proven dependability	Poor mixing and atomization No definitive characterization	Atomization (ref. 9)	Aerobee sustainer X-15 Pioneer
VARIABLE AREA (PINTLE)		Throttleable Proven dependability Simple to manufacture Large thrust per element	Wall compatibility problems No correlations for level of mixing and spray size	Generalized (ref. 10)	LEM descent engine Lance sustainer
SPLASH PLATE		Throttleable Insensitive to design tolerances Large thrust per element Proven dependability	Wall compatibility problems Relatively complex No correlations for level of mixing and spray size	Generalized (ref. 11)	Lance booster (early version) Saturn SIVB ullage control Apollo CM RCS (SE-8) Gemini SC maneuvering, attitude control, and reentry engines

*For circular orifices unless noted otherwise.

Table III. – Comparison of Typical Injector Elements for Gas/Liquid Injection

ELEMENT DESIGNATION	ELEMENT CONFIGURATION (FLOW DIRECTION)	ADVANTAGES	DISADVANTAGES	DESIGN CORRELATIONS*	ENGINE APPLICATION
UNLIKE TRIPLET (2 ON 1) ●○●		Excellent atomization Good overall mixing Resultant spray direction is axial	Wall compatibility is good only when fuel is used in outer orifices Sensitive to design tolerances Performance sensitive to continuous throttling	Mixing (ref. 12) Atomization (ref. 12)	None known
UNLIKE PENTAD (4 ON 1) ● ●○● ●		Excellent atomization Good overall mixing Applicable to extremely high or low mixture ratios or density ratios Well characterized	Difficult to manifold Wall compatibility problems Performance sensitive to throttling Tends to produce high heat flux to injector face	Mixing (ref. 12) Atomization (ref. 12)	None known
CONCENTRIC TUBE (WITH SWIRLER)		Excellent mixing and atomization Low pressure drop Proven dependability	Difficult to fabricate if annulus gap is very small (<0.06 in.) Tends to become unstable when throttled	Generalized (ref. 13)	J-2, RL-10, M-1 Russians use this element extensively
CONCENTRIC TUBE (WITHOUT SWIRLER)		Very good wall compatibility Low pressure drop Excellent atomization	Same as above	Mixing (refs. 5 and 14) Atomization (refs. 5 and 14)	
LIKE DOUBLET (1 ON 1) ● OR ○ ● ○		Easy to manifold Excellent for deliberate control of spray for wall temperature Good mixing Very stable element	Requires increased axial distances to mix the fuel and oxidizer Sensitive to design tolerances	None	None known

*For circular orifices unless otherwise noted.

2.1.1.1.1 Element Types

Elements can be divided into four categories: (1) unlike impinging, (2) like impinging, (3) nonimpinging, and (4) hybrid. The elements within each category differ in the method for mixing and atomizing the propellants. Some element types are more efficient in utilizing the available flow energy for mixing and atomization, but they do not necessarily provide spray distributions that are compatible with wall materials or stable combustion. Consequently, intelligent selection of an element or elements that will be best suited to a total injector concept requires a basic understanding of the behavior of the sprays produced by the various kinds of single elements.

Unlike-impinging elements. – These elements accomplish mixing and atomization by direct impingement of fuel and oxidizer jets. The impingement provides direct mechanical mixing by dissipative exchange of momentum. Virtually all of the mixing and atomization takes place in the immediate vicinity of the impingement point. Consequently, it is imperative that the elements be designed to provide "optimum" mixing in order to ensure achievement of the desired spray distributions. Since the mixing takes place near the point of impingement, ignition and chemical reaction occur near the injector face. Unlike-impinging elements therefore result in high heat flux to the injector face. In addition, with hypergolic propellants all unlike-impinging elements are subject to reactive stream separation (blowapart). The mechanisms governing this phenomenon are not well understood; however, blowapart is affected by injector geometric and hydraulic parameters and by propellant combination. Detailed studies of reactive stream separation are presented in references 15, 16, and 17.

The unlike-impinging doublet is the most common element used for storable-propellant engines. The dependability of the unlike-impinging-doublet element has been demonstrated in such diverse applications as numerous small reaction control engines and the Apollo LEM ascent engine. This element is composed of single oxidizer and fuel jets that impinge at a given angle at a prescribed distance from the injector face. The most commonly used impingement angle is 60° (45° and 90° angles have also been used). A schematic of a typical unlike doublet is provided in table II. This element is easy to manifold and simple to design. In addition, it can provide reasonably uniform mixing. When this element is employed near the combustion-chamber walls, then nonuniformities in local mixture ratio can cause chamber-durability problems. These problems generally are overcome by orientation of the element to provide axial flow of the spray after jet impingement and by showerhead fuel orifices in the outer ring to provide a fuel-rich, compatible environment near chamber walls.

The unlike-impinging triplet also has been used in production engines. The triplet element, as shown in table II, consists of two outer jets directed at a specific angle on a centrally located axial jet. Flow symmetry of the outer jets with respect to the central axial jets results in axially directed resultant spray under all operating conditions. Generally, this element is designed with the outer jets oxidizer and the central jet fuel. For this arrangement, the mass-flux profiles are dependent on operating conditions. For unbalanced jet momentum, extremely large variations in mixture ratio occur in the outer portions of the spray fan. Therefore, while it provides overall mixing uniformity slightly improved over that of the unlike doublet, the triplet may not be desirable for use near the chamber walls. To provide a more compatible atmosphere near chamber walls, designs with outer fuel and central oxidizer jets have been evaluated; these reverse designs reduced heat flux to the wall. In addition to its use with liquid/liquid propellants, this element has been studied for use with gas/liquid propellants. Experiments have shown that highly efficient atomization can be attained; however, mixture-ratio gradients still exist as with liquid/liquid propellants.

The unlike-impinging quadlet has been used rather extensively in space-vehicle engines. As shown in table II, this element is designed with four impinging orifices. The (a) version behaves very much like the unlike doublet. In the (b) version, the resultant spray direction after impingement is axial and is therefore insensitive to operating conditions, whereas in the (a) version the direction of the spray depends on the relative jet momenta.

The unlike-impinging pentad has been proposed for application but has not yet been used in a production engine. For liquid/liquid applications, this element is extremely attractive for engines operating at mixture ratios much different from one. The element is designed with four orifices equally spaced about a central axially directed orifice; all impinge at a common point (see the sketch in table II). The unlike-impinging pentad results in more nearly uniform mixing than the doublet or triplet. As with the other elements discussed, chamber durability is a problem with this element because of local mixture-ratio gradients. Two of the major disadvantages of this element are manifolding complexity and high heat flux to the injector face. Of all the unlike-impinging patterns, the pentad produces the highest injector-face heat flux. Designs placing the impingement point too close to the injector face have resulted in destruction of the injector. In addition to its use with liquid/liquid propellants, the pentad has been extensively studied for gas/liquid propellants. For gas/liquid application, this element provides highly efficient atomization and uniform mixing with relatively large thrust per element.

The ability to design the unlike-impinging elements to provide optimum spray distributions is contingent on having comprehensive design correlations that relate element mixing and atomization with injector geometric and hydraulic parameters. References for such correlations that exist are given for each element type in tables II and III.

The initial studies of liquid/liquid mixing characteristics for the unlike-impinging doublet are described in references 3, 7, and 18. These studies relate injector mechanical and hydraulic parameters to the resulting uniformity of mixture-ratio distribution. Subsequent investigations (ref. 6) included other unlike-impinging patterns (e.g., 2-on-1, 2-on-2, and 4-on-1). Reference 19 shows that the empirical equations developed in references 3, 6, 7, and 18 to describe the "optimum" injector design condition for uniform mixing are similar for all the unlike-impinging patterns.

Gas/liquid propellant mass and mixture-ratio distributions have been studied extensively (refs. 12, 14, and 20). Gas/liquid injector design correlations have been developed for the unlike-impinging triplet and unlike-impinging pentad (ref. 12).

For many years, dropsize characteristics for unlike-impinging jets were qualitatively implied through physical parameters such as orifice size and injection velocity. Some of the initial studies aimed at quantifying drop size produced by specific liquid propellant unlike-impinging double elements are described in references 8, 21, and 22. In the reference 8 study, a quantitative description of the atomization characteristics of unlike doublets and pentad injector elements was obtained. The reference-21 and -22 studies related parameters such as the orifice shape and dynamic pressure ratio of the impinging jets for unlike doublets and culminated in the most comprehensive and detailed study to date of drop size for liquid/liquid propellants (ref. 4). Both the mixing and atomization studies have shown that orifice diameter ratio, orifice size, impingement angle, and impingement distance affect the spray distributions for unlike-impinging elements.

Like-impinging elements. – For the like-impinging elements, atomization occurs as a result of dynamics of impingement in a manner analogous to that occurring with unlike-impinging elements. Mixing, however, is accomplished downstream of the jet impingement point, since the mixing occurs as a result of the intermixing of adjacent fuel and oxidizer spray fans. For these element types, the attainment of efficient mixing is related to the geometric arrangement of the fuel doublet relative to the adjacent oxidizer doublet. Design correlations for the like-impinging doublet with liquid/liquid propellants have been established (refs. 8 and 22). These studies have shown that the mass and mixture-ratio distributions are functions of element size, spacing between oxidizer and fuel fans, and fan inclination or cant angle. The geometric parameters are illustrated in figure 2. Note that the fans impinge on edge in this figure. This configuration has been found to provide excellent mixing uniformity and yet not result in reactive stream separation when hypergolic propellants are used. However, when the fans are designed to impinge on the broad side, significant blowapart occurs. Atomization studies have shown spray drop size to be a function of orifice size, injection velocity, impingement angle, and impingement distance.

Like-impinging doublets and sometimes triplets have been used in large LOX/RP-1 injectors. For example, the F-1, the Atlas first-stage booster and sustainer, and the first-stage Titan I engines utilize like-impinging doublets in various arrangements (table II). For these engines, the like-impinging doublets have been designed to provide uniformly mixed sprays as well as chamber compatibility. This objective is accomplished by designing the oxidizer and fuel elements in the core such that uniform mixing occurs, and by placing the outer fuel elements nearest the chamber wall with the outer oxidizer elements slightly inboard. This practice results in the core elements providing a high degree of mixing uniformity and the outer elements achieving a gradient in mixing from fuel-rich nearest the wall to oxidizer-rich near the core elements. This type of design minimizes overall mixing losses in comparison with normal boundary-layer cooling techniques that utilize showerhead fuel jets.

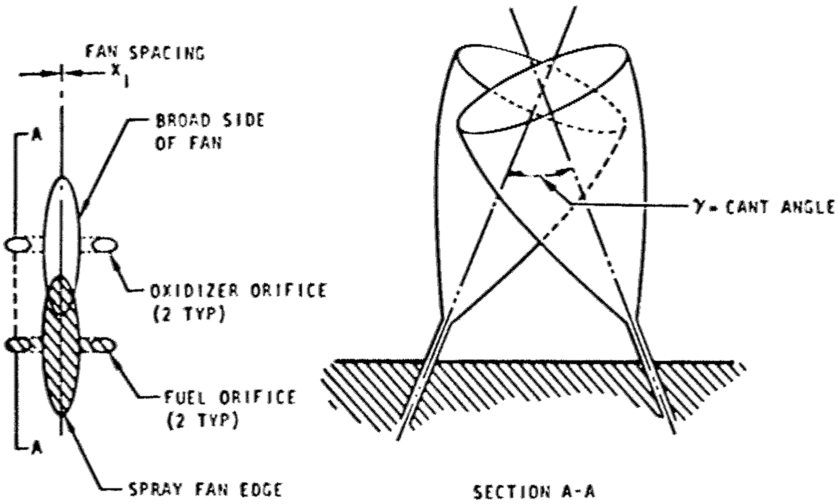


Figure 2. – Design variables for a like-impinging doublet.

Nonimpinging elements. – Nonimpinging elements include the showerhead and concentric tube. These elements have been used extensively in liquid/liquid and gas/liquid propellant applications (tables II and III). Mixing and atomization are controlled principally by the shearing of the liquid by the gas (either combustion gases or injected gaseous propellants).

The showerhead element was one of the first injector patterns used in a production engine. It was used in the German V-2 rocket, Aerobee sustainer engine, and one of the X-15 engines. In most current engines, the showerhead element is being used near chamber walls for film cooling; in this application, only a single propellant (normally fuel) is used. The showerhead is one of the simplest types of elements since it consists only of axially directed orifices. The mixing and atomization take place as a result of interaction of the combustion gases with the injected jets. Because of the low rate of mass transfer across the injector, the uniformity of mixing is primarily a function of the spacing between oxidizer and fuel jets. Close spacing of the jets insures that maximum mixing uniformity will occur. Since mixing relies primarily upon the turbulence generated during combustion, this element requires rather long chambers for complete mixing. No injector design study relating injector and hydraulic variables to mixing for liquid/liquid propellants has been conducted. However, studies to define dropsize characteristics, including the classic theoretical work by Rayleigh, have been conducted (refs. 9, 23, 24, and 25). Gas/liquid-propellant design correlations for atomization have been established (ref. 26). In general, the results show that the spray distributions are functions of orifice size, injection velocity, and spacing.

The concentric-tube element has been used extensively in both liquid/liquid and gas/liquid applications. For liquid/liquid applications, concentric-tube elements have been used in a candidate Surveyor vernier engine (MIRA 150A); and, interestingly, the Russians almost exclusively use the concentric-tube element with a swirler for all of their booster engines. For gas/liquid application, concentric-tube elements are used in the RL-10, M-1, and J-2 engines. Various types of concentric-tube elements have been built, including the flush-face (fig. 3(a)), the higher-performing recessed post (fig. 3(b)), and the higher-performing flush face with the oxidizer swirled by tangential entry (fig. 3(c)). Ribbon-type swirlers in the oxidizer post frequently have been subject to burnout during cutoff because hot gases were forced back across the low-heat-capacity swirlers, but tangential-entry swirlers have not been subject to this type of failure. Concentric-tube modifications for performance improvement have included directing the fuel inwardly rather than parallel to the oxidizer, chamfering the inside of the oxidizer post, and thinning the oxidizer post wall. Throttling capability of gas/liquid concentric-tube elements has been exceptionally good, particularly when potential stability problems are taken into account. Both recessed-post elements and swirl

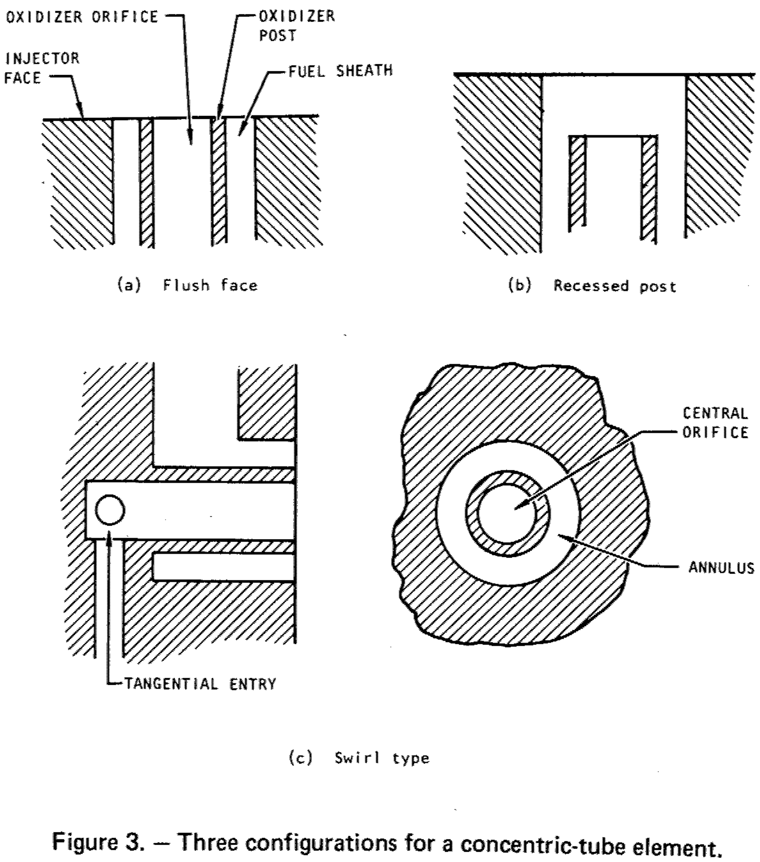


Figure 3. – Three configurations for a concentric-tube element.

elements have been successfully throttled over fairly wide ranges (refs. 27, 28, and 29). Although the geometry of the concentric-tube element appears to be relatively simple, it is in fact quite complex, and small changes in the geometry can result in significant performance and stability changes and variation in the heat transfer to the wall when these changes are made only in the outer row of elements. References 13, 29, and 30 contain basic design data on concentric tubes used with GH_2 and LO_2. References 31 through 37 are additional reports pertinent to concentric-tube design.

Hybrid elements. – Elements that do not fit conveniently into the above categories or are combinations of two or more of the above are classified as hybrids. These types include the pintle and the splash-plate injectors. Pintle injectors currently are used in the LEM descent engine and Lance sustainer engine. These injectors originally were subject to lowered performance, injector face burning, and wall streaking due to irregularities in upstream feed-system geometry and variations in local element mixture ratio under throttled conditions. The design of the pintle element is an inherent part of the overall injector design, and the problems encountered are intimately related to the details of the design. Design studies (refs. 10, 38, and 39) have resulted in understanding of the mechanisms controlling mixing and atomization to the extent that successful operation has been achieved.

The splash-plate injector has been used in many applications, including the early versions of the Lance booster engine and Gemini maneuvering engine. These elements have been used extensively at low thrust levels in production thrust-chamber assemblies where the total number of orifices was very small, primarily to improve ablative-wall durability and secondarily to reduce variations in performance induced by inadequate injector hydraulic control (refs. 40 through 42). Splash plates have also been used on larger production chambers in order to produce high performance with a very simple injector manifold system (refs. 11 and 43). Research and development programs for both thrust chambers and gas generators have involved extensive use of splash plates. Splash plates in general do not significantly increase performance for high-performance element patterns but are sometimes helpful with low-performance patterns. The primary problem with the splash-plate injector has been the burning of the splash plate when the oxidizer and fuel impinged above the splash-plate face. When the centerline impingement point of the propellant was at or below the splash-plate face, operation was satisfactory. A comprehensive study of the operation of the splash-plate injector is presented in reference 11. This study showed that performance is a function of splash-plate angle, gap, and injector orifice size.

2.1.1.1.2 Orifice Diameter and Diameter Ratio

Numerous studies (refs. 3, 7, 44, and 45) have demonstrated that the diameter of the element orifice d and the ratio of the diameters of the oxidizer and fuel orifices d_o/d_f (or other comparable dimensions for like and nonimpinging elements) control the mixing and atomization levels produced by the element. Orifice diameter ratio for unlike-impinging injector types has a strong effect on the level of mixing attainable. The specific effect, however, depends on the element type. For all element types, small orifices have consistently produced higher performance than large orifices, because the smaller droplet sizes result in increased vaporization rates and because mixture ratio is more nearly uniform. However, total heat flux to the injector face frequently is higher with small elements because of the higher combustion rate close to the face.

Unlike-impinging elements. – For unlike-impinging doublet elements flowing liquid/liquid propellants, the mixing correlation for circular orifice geometry presented in reference 3 shows that a specific diameter ratio is required for optimum mixing and that this ratio depends only on the propellant density and flowrate ratios. This correlation has been verified only up to a diameter ratio of 1.5. Experiments have shown that when the diameter ratio d_o/d_f differs significantly from 1.22, the level of mixing attainable with an unlike-impinging doublet suffers dramatically (ref. 3).

The correlation in reference 3 has been extended to noncircular orifice geometry for liquid/liquid propellants (ref. 5). It was found that the same general correlations apply if the diameter ratio is replaced with the orifice thickness ratios. The independent effect of thickness ratio on the level of mixing, however, is not known.

The cold-flow characterization of the unlike-impinging triplet is relatively meager. Reference 6 presents an optimum-mixing correlation for the triplet element flowing liquid/liquid propellants; however, the reference suggests that the correlation be used only when the ratio of center stream diameter to outside stream diameter is approximately 0.79. For gas/liquid propellants, generalized mixing correlations have been developed (ref. 12). Mixing uniformity was found to be a function of the penetration of outer liquid jets into the central gas jet.

The unlike-impinging pentad has been used primarily in research and development programs. Correlations for optimum mixing of liquid/liquid propellants are presented in reference 6.

Reference 19 presents a correlation relating the orifice area ratio for maximum mixing efficiency for all of the above unlike-impinging elements when designed for an included impingement angle of 60°. The correlation was based on the results of the cold-flow studies of element mixing efficiency (refs. 8, 15, 22, and 46) and was confirmed by cold-flow studies of a 3:1 element. This correlation can be written (adptd. from ref. 19)

$$\left(\frac{d_c}{d_{ou}}\right)^2_{MME} = M\left[\frac{\rho_{ou}}{\rho_c}\left(\frac{\dot{w}_c}{\dot{w}_{ou}}\right)^2\right]^{0.7} \tag{1}$$

where, with any set of self-consistent units,

d_c = diameter of the center orifice (for 1:1 and 2:2, either side-by-side or opposed, the "center" orifice is assigned arbitrarily to either leg and the area is that of an individual orifice)

d_{ou} = diameter of outside individual orifice

M = mixing factor determined from experiment (typical values given in table IV below)

ρ = liquid density

$\dot{w}_c$ = total mass flowrate through all center orifices

$\dot{w}_{ou}$ = total mass flowrate through all outside orifices

subscript MME = maximum mixing efficiency

Table IV. – Values of Mixing Factor M for Several Types of Element

Element Type	M
1-on-1, 2-on-2	1.0
2-on-1	1.6
3-on-1	3.5
4-on-1	9.4
5-on-1	27.5

For a given propellant combination, the flowrate and density ratios are fixed and the only remaining independent variable in equation (1) is M, a constant for a specific element type. Therefore, after selection of propellants, equation (1) is used to define the diameter ratio d_c/d_{ou} that produces optimum mixing for each element type.

With the propellants and diameter ratio specified, the ratio of oxidizer-to-fuel pressure drop can be calculated. From overall system considerations, it is undesirable to have the pressure drops for fuel and oxidizer widely different; thus the final selection of element is affected by the calculated ratio of the pressure drop across the fuel orifice to the drop across the oxidizer orifice. Even though equation (1) specifies optimum configurations, the independent effect of diameter ratio on the level of mixing attainable for the "optimum configuration" is not specified. Very little information on diameter-ratio effects is available; limited data on this effect for unlike-doublets are given in reference 3.

The size of the orifice also affects the level of mixing. Studies have shown that the smaller the element, the higher the level of mixing (ref. 8). However, for orifice sizes below 0.020 to 0.030 in., little improvement is seen. For hypergolic propellants, large orifices ($d > 0.03$ in.) result in reactive stream separation, whereas little effect is observed for small orifices ($d \leqslant 0.03$ in.).

Atomization studies (refs. 4, 8, 21, and 22) have shown that both the orifice diameter and diameter ratio influence drop size; in particular, the smaller the jet diameter, the smaller the drop size. This relation is apparent in the following expression, developed for unlike-doublet elements having 60° included impingement angles (adptd. from ref. 4):

$$\bar{D}_f = 2.9 \times 10^4 \; V_f^{-0.766} \left(\frac{P_c}{P_j}\right)_f^{-0.65} d_f^{0.293} \; P_D^{0.165} \left(\frac{d_o}{d_f}\right)^{0.023} K_{prop} \tag{2}$$

where

$\bar{D}$ = mass median drop size, microns

V = injection velocity, ft/sec

$\dfrac{P_c}{P_j}$ = velocity profile parameter, dimensionless

P_c = dynamic pressure at center of jet, psi

P_j = mean dynamic pressure of jet, psi

d = orifice diameter, in.

P_D = dynamic pressure ratio $\rho_f V_f^2/\rho_o V_o^2$, dimensionless

K_{prop} = correction factor for propellant physical properties

ρ = density, lbm/ft^3

subscript o, f = oxidizer and fuel, respectively

To date, little has been done to relate the propellant physical properties to drop size. The following expression for physical-property correction factor K_{prop} was suggested in reference 47:

$$K_{prop} = \left[\left(\frac{\mu \sigma}{\rho} \right)_{propellant} \bigg/ \left(\frac{\mu \sigma}{\rho} \right)_{Shellwax\ 270} \right]^{1/4} \quad (3)$$

where

μ = dynamic viscosity, lbm/(ft-sec)

σ = surface tension, dynes/cm

(For the reference material Shellwax 270, $\mu = 2.69 \times 10^{-3}$ lbm/(ft-sec), σ = 17 dynes/cm, and ρ = 47.7 lbm/ft^3.)

Expressions similar to equation (2) have been developed for the other unlike-element types (refs. 4, 8, and 21).

Like-impinging elements. – For these elements, the orifice sizes of the impinging jets are equal and, therefore, the diameter ratio is not a parameter. The actual size of the jets, however, does affect both the mixing and atomization levels. As with the unlike-impinging patterns, the smaller the orifice, the more uniform the resulting spray. Experiments have shown that, for elements with jets smaller than 0.03 in., no significant increase in mixing occurs. As shown by the following equation (adptd. from ref. 4), orifice size has a rather strong effect on atomization for the like-impinging doublet (60° included impingement angle):

$$\bar{D} = 1.6 \times 10^5 \ V_f^{-1} \left(\frac{P_c}{P_j} \right)^{-0.10} d_j^{0.57} \ K_{prop} \quad (4)$$

where

V_j = mean jet velocity, ft/sec

d_j = jet diameter, in.

Here, drop size is roughly proportional to the square root of the orifice diameter.

Non impinging elements. – The ratio of orifice diameters has no effect on mixing or atomization for the showerhead element. However, the size of the element does affect both mixing and atomization. Mixing for showerhead jets increases for smaller jets, since for a fixed total flow area smaller jets result in increased total surface area. No correlations that show this effect quantitatively are available. Generally, the orifices are made as small as possible, consistent with fabrication limits. For free jet flow, where the surrounding medium affects the breakup process, jet size is directly proportional to drop size (ref. 9). Therefore, decreasing element size increases performance for vaporization-limited combustion.

For the concentric-tube element, the equivalent of diameter ratio is the ratio of the width of the annulus gap to diameter of the center jet. Element size is equivalent to the center-jet diameter. Experiments have shown that mixing decreases when the ratio of annulus width to center-jet diameter increases. This effect is thought to be related to increased loss in flow energy available for mixing as a consequence of outward expansion of the flow from the annulus jet (i.e., for this type of design, increased thickness increases outer surface area). In addition, increased size also results in a decrease in mixing uniformity. Empirical correlations of the element geometry quantitatively with variations in mixing and atomization are presented in references 5 and 14. An analytical model has been developed specifically for O_2/H_2 propellants (ref. 48). This model defines the liquid-jet stripping, atomization, and combustion processes for a concentric-tube injector element. Some success has been achieved in applying the reference-48 model to actual engine data of reference 49. The results from the reference-48 analysis have also been input to stability models (ref. 50), and stability trends have been predicted successfully. A considerable quantity of experience, however, has been gained from engine development programs relating variations in orifice element design to changes in heat flux to the wall or in overall engine performance. In reference 14, for example, it was shown that the relative velocity or differential velocity between the gas in the annulus and the liquid in the center jet is of critical importance in attaining performance and stability; in addition, empirical correlations among differential velocity, performance, flow per element, chamber pressure, and other minor variables were developed. As another example, high-performance designs resulting in low ΔP have been found insufficient for distributing the liquid oxidizer in the feed manifold and sometimes insufficient to meet system stability requirements. To overcome the problems resulting from low ΔP, a small orifice for flow control is placed at the forward end of the center liquid tube (i.e., at the manifold outlet into the tube), with a large outlet area at the exit end of the tube to inject the liquid at low velocity.

Hybrid elements. – For the pintle element, the equivalent of diameter ratio is the ratio of the inner to the outer annulus or, in the case of the LEM descent engine, the ratio of the width of the outer annulus A to the width of the inner slot S (fig. 4). The most definitive works on the pintle injector are those of references 10 and 39. Experiment has shown that a correlation very similar to that for unlike injectors also applies to the pintle design; i.e., a momentum balance between the inner stream and the outer stream produces optimum mixing.

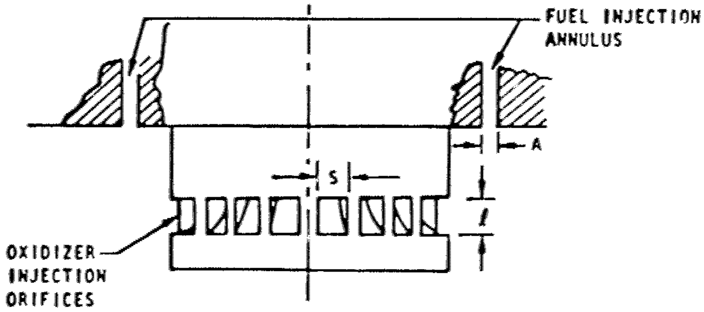


Figure 4. – Illustration of pintle element showing inner slots and outer annulus.

For liquid/liquid applications, the correlation for oxidizer injected through slots in the pintle is expressed as (adptd. from ref. 10)

$$\frac{\rho_f V_f^2 \ (AS + 2\,\ell C)}{\rho_o V_o^2 \ S\ell} = 1 \qquad (5)$$

where

A = width of the fuel slot (annulus), in.

S = width of oxidizer slot, in.

ℓ = length of oxidizer slot, in.

C = cross-influence term (defined in ref. 10), in.

It should be noted that the same expression has been found to apply also to gas/liquid designs (ref. 38).

In the splash-plate injector, the jets impinge on a plate, and hence there is little if any dependence of the mixing uniformity on orifice diameter ratio. Orifice size, however, does affect both atomization and mixing. In reference 11, it is shown that the overall performance increased as the orifice size was increased until the oxidizer jet diameter was 0.08 in.; then, with further increases in the size, performance decreased. The specific roles of atomization and mixing were not determined. These results suggest that there is a tradeoff between these two parameters when the element size is increased. Studies of the effect of jet size on atomization for jets impinging on a plate (refs. 51 and 52) suggest that as the jet size increases, drop size also increases.

2.1.1.1.3 Impingement Angle

The angle of impingement between impinging jets affects propellant backsplash, resultant mixing uniformity, and atomization characteristics. Propellant backsplash on the injector face can result in injector-face burnout. The relative importance of impingement angle depends on the element type.

Unlike-impinging elements. – For unlike-impinging elements, the greater the impingement angle, the greater the quantity of mixed propellant flowing back toward the injector face. The phenomenon of mixed propellant backflow is illustrated in figure 5.

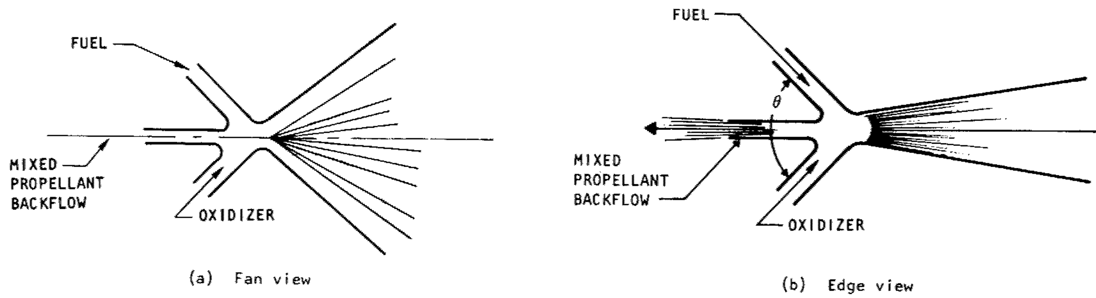


Figure 5. – Two-dimensional flow field for a typical unlike-impinging element.

It is easily shown that the quantity of mass flowing backward is proportional to the cosine of the impingement half-angle. In addition, the angular distribution of mixed spray leaving the point of impingement is also dependent on impingement angle: the greater the impingement angle, the greater the mass distributed at angles greater than 90°. Experiment has shown that impingement angles $\geqslant 90°$ result in high heat flux to the injector face.

Mixing uniformity is also affected by impingement angle. For liquid/liquid propellants, this effect has only been quantitatively defined for unlike-impingement doublet elements (ref. 3). The results show that over the range of impingement angle from 80° to 40°, mixing increases as the impingement angle decreases. Impingement angle also affects the mixing uniformity for gas/liquid propellants. For gas/liquids, the impingement angle θ producing optimum mixing may be related to the flow conditions by the expression

$$\cos(90^\circ - \theta) = 0.2 \; \frac{V_g}{V_L} \; \frac{d_g}{d_L} \left(\frac{\rho_g}{\rho_L} \right)^{1/2} \tag{6}$$

This expression defines the optimum mixing for two opposed liquid jets penetrating into a central gaseous jet. Similar expressions are available for other configurations (refs. 12 and 20). Impingement angle should also affect drop size; however, for unlike-impinging elements, this effect has not been determined. Most unlike-impinging injectors have been designed with impingement angles of 60°

Like-impinging elements. – For the like-impinging doublet, backsplash is not as serious a problem as it is with unlike elements, because the propellants are not physically mixed until the spray fans intermix. Consequently, the propellants that strike the face are not burning. It should be noted that the same general flow patterns exist with the like as with the unlike patterns.

The like-doublet design (fig. 2) has a primary impingement angle (included angle between two oxidizer or two fuel jets) and a cant angle (included angle between the centerlines of the oxidizer and fuel fans). The mixing is not affected by changes in the primary impingement angle. Studies of the effect of the primary impingement angle on drop size for like-impinging jets are reported in references 4, 53, and 54. References 4 and 54 agree that the relation can be expressed as

$$\overline{D}_\theta = (1.44 - 0.00734\,\theta)\;\overline{D}_{60} \tag{7}$$

where θ is impingement angle expressed in degrees and $\overline{D}_{60}$ is the value for drop size obtained from equation (4).

As shown in the foregoing expression, drop size decreases linearly with increasing impingement angle. As with the unlike elements, most like-doublet elements have had primary impingement angles of 60°. Ninety-degree impingement has been used to a lesser extent.

The cant angle has a significant effect on mixing. Experiment has shown that increasing the angle from 0° to 41° increases mixing uniformity by about 30 to 40 percent. Further increases can cause a decrease in mixing uniformity (ref. 4).

Non-impinging elements. – Impingement angle does not apply to the showerhead element. The equivalent of impingement angle for the concentric-tube injector is the inner-post chamfer angle, illustrated in figure 6. The angle of chamfer causes the liquid inner flow to spread into the gas. However, if the liquid separates, the post can be burned. Chamfer angles of about 5° generally have been used; however, angles up to 90° have been evaluated.

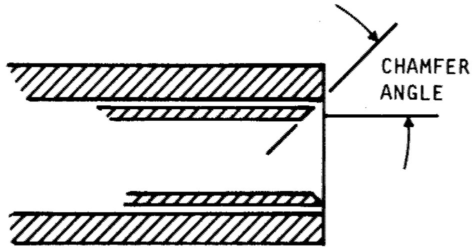


Figure 6. — Illustration of inner-post chamfer angle in a concentric-tube element.

Hybrid elements. – The equivalent of the impingement angle for the pintle injector is the pintle deflector angle (fig. 7). The deflector angle is extremely important to this design. For a given set of flow conditions, if the deflector angle is too great, the oxidizer can impinge on the chamber wall, producing high heat flux to the wall and, for ablative chambers, wall erosion. Also, the impingement process can result in back flow of propellants; the quantity of back flow is related to the deflector angle. In another pintle design, the oxidizer is injected radially from the pintle through slots, as depicted in figure 4. For this case, the impingement angle is the angle between the axis of the slot and the deflector. The LEM descent engine is designed with an angle of about 90°.

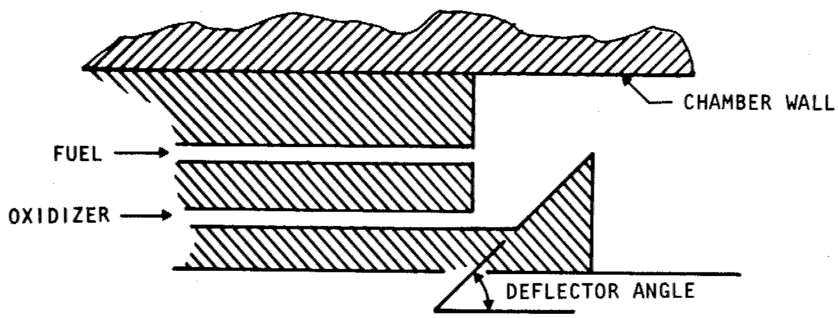


Figure 7. — Illustration of pintle deflector angle.

For the splash-plate injector the equivalent of impingement angle is the splash-plate angle (fig. 8). Reference 11 shows that increasing the splash-plate angle from 20° to 27° has

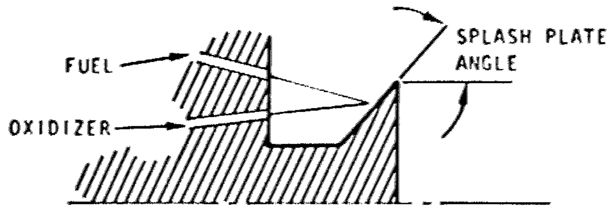


Figure 8. – Illustration of splash-plate angle.

essentially no effect on the performance. It is uncertain whether further increases in splash-plate angle would affect atomization or mixing uniformity.

2.1.1.1.4 Impingement Distance

The impingement distance or free-stream jet length is the length of the jet from the orifice exit to the point of impingement measured along the jet centerline. For all impinging element types, long free-stream jet lengths result in the impingement of streams that are already partially disintegrated. This effect can result in misimpingement of jets. In addition, initial stream misimpingement caused by fabrication tolerances is amplified by the ratio of free-stream length to orifice diameter L_{fs}/d_{or}. Large values for this ratio ($\geqslant$ 10) magnify the effects of stream misalignment caused by poor orifice geometry, poor feed system geometry, transverse winds, or poor geometric centerline impingement. The result is wall streaking and reduced performance. Some types of instability also have been attributed to poor propellant stream impingement. Low values of L_{fs}/d_{or} ($\approx$ 5 to 7) produce far fewer hardware problems as a result of stream misimpingement.

Unlike-impinging elements. – Data in reference 55 show that misimpingement has a strong effect on mixing uniformity, i.e., a 20-percent variation in the misimpingement of the jet centerline causes a 15-percent change in mixing uniformity. In addition, the resulting spray fan is rotated approximately 90° from that of the "perfect" impingement jets. Reference 55 also shows that the resulting drop size is sensitive to misimpingement. However, for unlike-impinging elements, the effect has not been quantified. For solid-face injectors, most opposed impinging elements can be made with low values for L_{fs}/d_{or}. With ring-type injectors that are sealed at the face by brazing or welding, low values are harder to obtain. Doublets and side-by-side 2:2's can still be made with relatively low values for L_{fs}/d_{or} without drilling through the joints, but triplets, opposed 2:2's, and 4:1's result in high values.

Like-impinging elements. – For doublets close to the chamber wall, high values for L_{fs}/d_{or} cause misimpingement and result in wall erosion caused by rotation of the spray fan into the chamber wall. Since the like doublet is designed to have adjacent fuel and oxidizer fans mix, then any rotation of one fan relative to another can result in reduced interspray mixing.

Excessive values for L_{fs}/d_{or} can also cause an increase in spray drop size (ref. 4). Maximum impingement distances of 5 to 7 times the jet diameter result in a minimum change in drop size. Significant differences can occur when $L_{fs}/d_{or} < 10$.

Nonimpinging elements. – Impingement distance is not a design parameter for showerhead injector elements. For the concentric-tube element, the equivalent of impingement distance is the recess depth of the inner tube. Recess results in improved mixing and atomization for gas/liquid concentric-tube injectors; data have shown that recess depth equal to one center-post diameter results in a maximum value of mixing and minimum drop sizes (refs. 5 and 14). Decreasing or increasing the recess from this value reduces mixing uniformity and increases drop size. This effect may be influenced also by the mixture ratio; however, there are insufficient data to support this proposition. For noncircular elements, similar results for the effects of recess depth are found (ref. 5).

Hybrid elements. –The ratio L_{fs}/d_{or} has been found to affect both performance and stability for the pintle injector; however, no specific design correlations have been defined. For the splash-plate injector, L_{fs}/d_{or} is not a design parameter.

2.1.1.2 ELEMENT ARRANGEMENT

The element arrangement involves two considerations. First, the position of elements with respect to one another should result in increased overall mixing uniformity because of interelement mixing. In addition, the placement of the elements across the injector face should ensure uniform mass distribution. This is an important requirement because maldistribution of mass can result in radial and transverse winds. Secondly, the orientation of the element with respect to the chamber wall should provide a combustion environment near the wall that will not affect hardware durability. Improper element arrangement therefore can produce both lowered performance and reduced hardware durability.

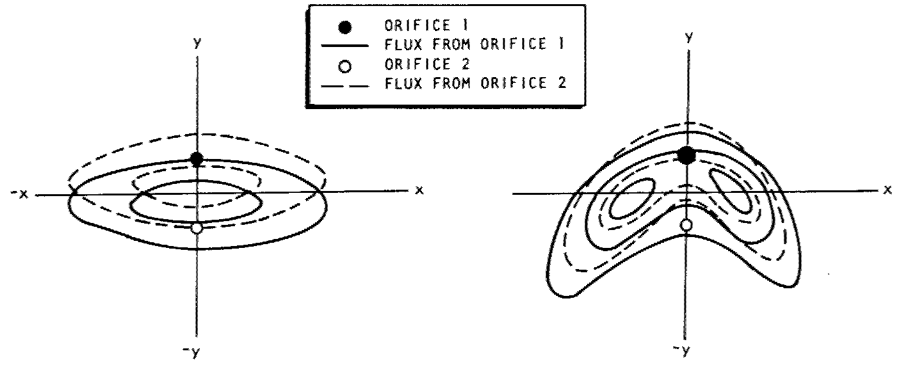
2.1.1.2.1 Element Distribution

If the mixing produced by a single element were perfectly uniform, then additional uniformity could not be brought about by mixing of sprays from adjacent elements. All elements in use today produce some mixture-ratio gradients across the element spray, and consequently the position of one element with respect to another can affect mixing uniformity. (It should be noted that improper placement can result in large regions of poorly mixed sprays.) Typical spray mass distributions for an unlike-impinging doublet, triplet, and pentad element at differing flow conditions are shown in figures 9, 10, and 11. Note that wide variations in mixture ratio occur within the spray fans. For several of these elements, judicious placement of elements can result in increased mixing; in others (4-on-1), the symmetry of the flow field precludes any advantage from interelement mixing. In addition, for the unlike doublet, the wall compatibility characteristics are very sensitive to position and operating conditions, because the fan spray pattern is sensitive to variations in stream momentum ratio (fig. 9). As illustrated in figure 10, for the unlike-impinging triplet the resulting spray pattern is considerably less sensitive to injector flow conditions. Note that the spray direction will always be axial and that the general shape of the fan is unchanged.

For the pentad element, if the momentum of the outside streams is too low (fig. 11(a)), the center stream will not be penetrated adequately and gas mixture-ratio gradients will occur. If it is too high (fig. 11(b)), the outside streams will impinge at the element centerline, the center stream will be forced outside, and again gas mixture-ratio gradients will result. The 4-on-1 element is essentially a primary mixer with good symmetry and is almost independent of secondary mixing, so that element spacing becomes relatively unimportant in performance optimization.

It is obvious from these examples that rather large variations in mixture ratio can and do occur within a spray fan produced by an element. Even for optimum-design configurations, rather large variations in mixture ratio can occur.

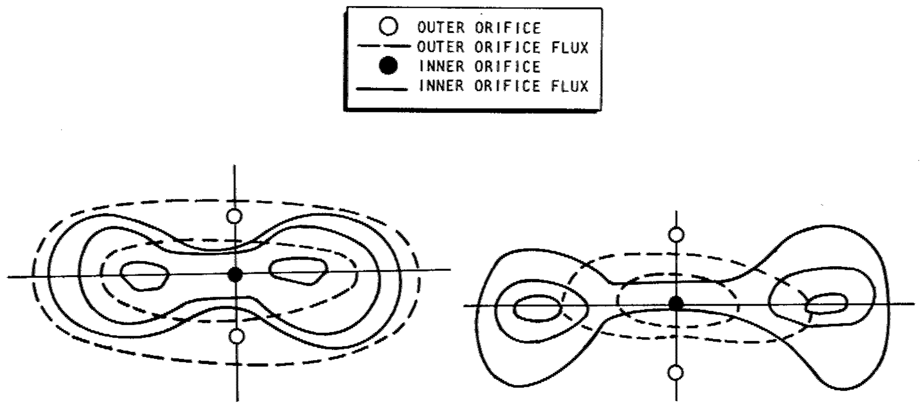
The propellant-mixture-ratio asymmetry of the opposed-impingement doublet normal to the fan axis (fig. 9) allows the use of secondary mixing obtained through interelement spacing to improve the performance of this primary mixing element. Figure 12(a) shows an arrangement used to increase secondary mixing and compensate for incomplete primary mixing; the same basic opposed-doublet element arranged as in figure 12(b) tends to perpetuate any primary mixing deficiencies with resultant loss in performance. With its symmetry normal to the fan axis, the opposed triplet (fig. 10) does not benefit much from secondary mixing; there is little information available on its performance as a function of interelement orientation. As noted, the 4-on-1 element (fig. 11) provides highly uniform primary mixing, and therefore mixing is a very weak function of orientation for reasonably-well-optimized configurations. The circumferentially symmetric concentric-tube element produces practically all of its performance as a result of the individual element configuration, and its performance is almost completely independent of interelement location. Performance for the pure self-impinging doublet depends completely on secondary mixing, and is strongly dependent on oxidizer-element-to-fuel-element fan spacing. In general, the more symmetric the element is, the less influence the interelement positioning has on performance. Highly symmetric elements tend to be easier to optimize in terms of performance, since many of the variables involved are essentially eliminated.



(a) Equal diameters and equal stream momenta

(b) Unequal diameters and equal overall stream momenta

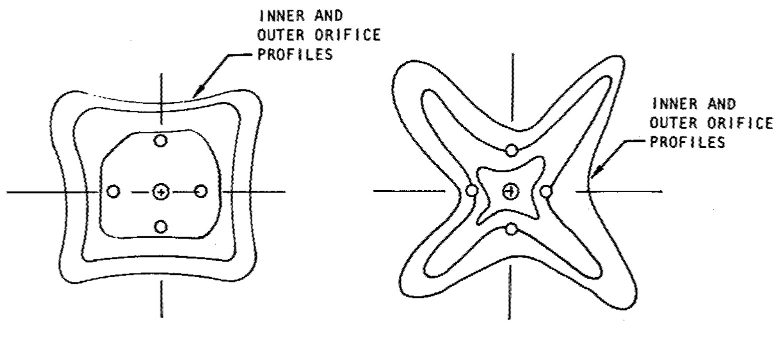
Figure 9. – Effect of orifice diameter on mass-flux contours for an unlike-impinging doublet.



(a) Inner and outer jets momentum balanced

(b) Outer stream momentum much greater than inner stream momentum

Figure 10. – Effect of stream momentum balance on mass-flux contours for an unlike-impinging triplet.



(a) Moderate momentum ratio

(b) High momentum ratio

Figure 11. – Effect of momentum ratio on mass-flux contours for a four-on-one element.

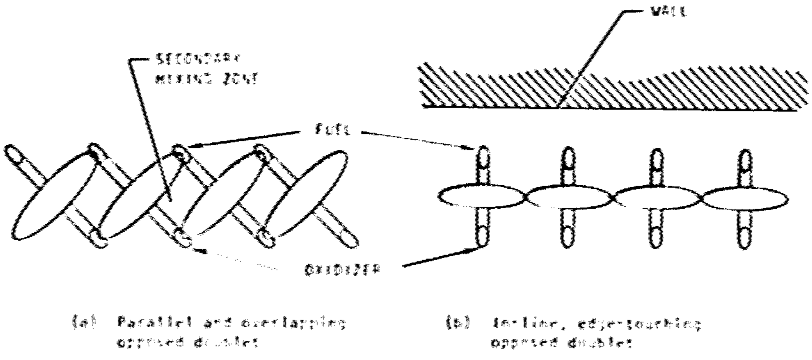


Figure 12. – Spray patterns of opposed-doublet elements.

Hardware durability problems have been at a minimum with injectors that produced uniform mixture-ratio distributions both near and away from the walls. However, radial and transverse winds produced by gross mass and mixture-ratio maldistributions have caused severe overheating and erosion of injectors, chamber walls, and baffles. For example,

- Unacceptable wall streaking in an ablative chamber in an early LEM ascent engine resulted from excessively high mass flowrate in the central portion of the injector.
- On the F-1 engine, injector-face erosion within baffle compartments and wall overheating resulted from nonuniform compartment mass flowrate.
- An early version M-1 gas generator that flowed more than one hundred pounds per second of propellants through only four injector elements suffered catastrophic face burning from the highly concentrated, poorly distributed mass flows.
- On the Atlas engine, injector patterns of the "wagon wheel" type, which produce radial paths leading to the wall that are free of injected propellants, produced injector overheating and erosion along those radial paths.

In each of these instances, the problem was corrected by altering injector element arrangement to achieve a better distribution of mass flowrate. In some cases, however, mass and mixture-ratio maldistribution is intentionally designed into the peripheral region of the injector to reduce heat transfer to the chamber walls. In the J-2 engine, for example, increasing the mass flowrate to the outer elements of the injector produced a high pressure region that caused gases to flow radially inward and thereby decreased the heat transfer to the wall; complete removal of the outer-row elements increased the heat transfer considerably.

2.1.1.2.2 Element Orientation

Element orientation can influence the rate of heat transfer to the walls and baffles. With elements placed on a circularly oriented feed system in circular chambers, orientation of the element with respect to the wall usually is constant, and any local variations in wall durability from element to element normally result from causes other than element orientation. However, with a noncircular feed system, baffles, or a rectangular chamber, element orientation can introduce large variations in local wall durability. These variations have led to wall and baffle burning and have sometimes required a considerable amount of local element adjustments to produce a satisfactory design. With elements that are oriented identically in relation to the wall, a single specific change to the element results in consistent changes in wall durability. With elements with differing orientation in relation to the walls, individual changes for each orientation or variation must be worked out. The use of a completely symmetric element such as the concentric tube generally eliminates the element-orientation problem.

Baffles are particularly prone to local overheating, since normally the elements are oriented for performance and chamber wall compatibility rather than for baffle compatibility. A staggered baffle-to-element spacing produces more local heat-transfer variation than does uniform spacing. The partial impingement of mixed propellant streams, droplets, or combustion products from outer-zone elements against surfaces as a result of improper orientation frequently have caused overheating of chamber walls, baffle walls, and injector faces. Outer-zone opposed-impingement doublets oriented toward the wall normally will produce higher heat fluxes (not necessarily at the point of impingement, but sometimes downstream) than will an orientation in which the direct impingement is greatly reduced. Various injector elements ranging from concentric tubes to several types of opposed impingement elements have produced local wall overheating when the propellants were directed toward the wall. Redirecting the element parallel to the wall produced less mixed propellant impingement on the wall and normally resulted in less wall streaking than elements with the fans at right angles to the wall. Experience with the XLR-129 (main burner) and the M-1 injector showed that canting the elements inward (toward the engine centerline) resulted in lowered local heat flux to the chamber wall. In addition, for concentric-tube injectors with swirlers, experience with the XLR-129 (preburner and mainburner injectors) demonstrated that, for the outer row of elements, scarfing the element from the outboard (chamber wall) side of the tube to a point flush with the injector face on the inboard side of the tube reduced the heat flux to the chamber wall. Splash plates operate satisfactorily with mixed propellant impingement because normally the splash plate is flooded with enough propellant to cool the plate.

2.1.1.3 COMBUSTION STABILITY CONSIDERATIONS

Combustion instability, or oscillatory combustion, has been an important consideration in the development of nearly all production rocket engines. Instability was a significant problem, for example, in the RS-1401 PBPS engine with a thrust of 300 lbf and in the F-1 engine with a thrust of 1.5×10^6 lbf. Other engines in which stability was an important factor in design include Atlas, Thor, H-1, J-2, J-2S, Apollo SPS, LEM Ascent, Lance (booster and sustainer), Titan Gemini, and Titan III Transtage. The nature of combustion instability and methods for preventing it are discussed in detail in references 56 and 57.

Combustion instability results from an oscillatory coupling of the combustion process and fluid dynamics; this coupling is determined in large measure by the injector. Because instabilities are detrimental to the operation of a rocket engine and often result in catastrophic failure, usually no form of instablity can be permitted. Thus, the injector designer must consider the features of the injector design that affect stability.

The methods for controlling or eliminating combustion instability vary with the type of instability present or expected. Several types of instability can occur, the particular kind depending on the relative importance of various oscillatory processes. Four basic types are as follows:

(1) Chug instability, which occurs with frequencies typically in the range of 50 to 250 Hz. This form of instability results from a strong coupling of the feed system and the combustion chamber. The oscillation in the elements of the feed system and the combustion chamber may be considered spatially uniform but time varying.

(2) Buzz instability, which occurs with frequencies typically in the range of 100 to 900 Hz. Again, the coupling of the feed system with the combustion chamber is pronounced. However, the wave character of the oscillations in the feed system is important in this case, but the combustion chamber oscillation may still be regarded as spatially uniform.

(3) Acoustic instability, which occurs with frequencies > 500 Hz. With this form of instability, the oscillation is dominated by the wave behavior in the main chamber (with spatial variations), and coupling with the feed system is negligible.

(4) Hybrid instability, which also occurs with frequencies typically > 500 Hz. This oscillation is strongly coupled between the feed system and the combustion chamber. In addition, the wave character of the oscillation is significant in both the feed system and the main chamber.

Chug and buzz instabilities usually are controlled through adjustments to the feed system, the injection passages, or element characteristics. Hybrid instabilities are controlled in the same manner.

Acoustic instabilities generally are eliminated through the use of suppression devices in the combustion chamber; the design and application of these devices is described in reference

58. In addition, the characteristics of the injector itself can be adjusted to promote stability; e.g., the size of the injection element may be changed or the mass and mixture-ratio distribution may be modified.

Feed-system-coupled instabilities. – These modes of instability often are analyzed, and remedial measures devised, on the basis of analytical models for the system. This is particularly true for the lower-frequency instabilities, which are more tractable to analysis. Principally these analyses allow estimation of the response of various portions of the system to oscillations in chamber pressure. Such models may be used to indicate changes in an injector design that will prevent feed-system coupling. Analytical models and techniques are described in references 59 through 61.

These models, and experience as well, indicate that the injector passages should be designed with as large a pressure drop (ΔP) and orifice length as practical. The required pressure drop for the fuel and oxidizer injection elements to prevent chug instability has been found to vary with the element type, minimum values of $\Delta P_{inj}/P_{ch}$ of 5 to 20 percent generally being found.

With concentric-tube elements, pressure-drop limits of $\Delta P_{inj}/P_{ch} \approx 5$ percent have been obtained. With unlike-impinging elements, $\Delta P_{inj}/P_{ch} \approx 10$ to 15 percent is typical. Like-impinging elements have been found to require approximately 15 to 25 percent. The pressure-drop requirements have been minimized by tailoring the orifice lengths and manifold volumes.

In the case of higher frequency feed-system-coupled modes, analytical models have been used to guide installation of orifices, dams, and resonators in injectors to prevent such modes. For example, in the booster engine for the Extended Range Lance, dams placed in the injector ring grooves successfully eliminated a hybrid-type instability. In the J-2S engine, inserts placed in the oxidizer posts of the concentric-tube injection elements successfully eliminated a hybrid-type instability. Both of these solutions for instability were developed through the use of detailed and extensive analytical modeling and experimental studies.

Feed-system-coupled instability problems are accentuated in engines that must be throttled.

Some feed-system-coupled instability problems have been attributed to two-phase flow as a result of excessive heat transfer. This phenomenon has been eliminated by increasing the manifold pressure.

Acoustic instabilities. – The design of an injector often is affected by the use of stabilization devices to prevent acoustic instability, because these devices frequently are mounted on the injector or form an integral part of it. For example, the injection pattern may be dictated in part by a baffle arrangement mounted on the injector face; also, injection elements at the downstream end of the baffle may be required to avoid a significant loss in performance. Special mixture-ratio bias or film cooling may be required. Injector design also may be affected by a requirement to install a stability rating device (e.g., a bomb) on the injector face.

The injector has a direct influence on acoustic instability because of its influence on the combustion flow field. Analytical models such as Priem's (ref. 62) demonstrate the dependence of stability on such injector-defined parameters as droplet sizes, local relative velocities between the droplets and gases, and burning rate. Such models may be used in conjunction with steady-state combustion models to assess the influence of injector design parameters on stability. Unfortunately, many changes that tend to improve performance also degrade stability. The analytical models of references 63 and 64 have been most widely used.

Stability also is affected by the injector-defined propellant mass-flux distribution. Essentially, the propellant mass is concentrated in regions of the chamber where the acoustic mode cannot couple efficiently with the combustion. This approach has been proved to be effective in promoting stability (refs. 65 through 68).

Although stability (acoustic) can be improved by adjustments to the injector configuration, this configuration usually is determined on the basis of other considerations, and stabilization devices are used to obtain the required stability (ref. 58).

2.1.2 Individual Orifice Geometry

Establishing the individual orifice geometry is one of the major steps in constructing the total injector flow system. This step follows in logical order after the total element pattern has been formulated.

The theory for predicting individual orifice stream characteristics such as flowrate, stream direction, or stream "bushiness" is not well developed for orifices under the operating conditions and physical constraints of most rocket engine injectors. The orifice variables that must be accounted for in any general theory include physical characteristics (e.g., orifice bore diameter, bore length-to-diameter ratio L/d, roughness, inlet geometry, and exit contour) and fluid or hydraulic characteristics (e.g., propellant properties, orifice pressure drop, back pressure, back pressurant, and propellant cross velocity (stream flow direction, velocity, and orifice inlet angle)). The most important flow-controlling aspects of the orifice geometry and the ones with which most problems occur are the orifice inlet geometry, the bore, the exit contour, and the related tolerances necessary for reproducibility.

Uncontrolled or nonreproducible orifice-stream hydraulic characteristics associated with either orifice design or orifice fabrication techniques have been responsible for many injector failures and engine operational problems. Examples of such problems include (1) hydraulic flip*, with a resultant increase in injector pressure drop and concurrent thrust dropoff, (2) chamber wall streaking and overheating because of orifice inlet or outlet burrs in the peripheral elements, (3) large variations in injector pressure drop resulting from inadequate control of the orifice inlet contour or orifice diameter, and (4) low orifice bore length-to-diameter ratio resulting in element misimpingement with subsequent wall streaking or reduced performance, particularly with high cross velocities behind the orifices.

Comprehensive work on orifice flow characteristics is presented in references 69, 70, and 71; these references also contain a complete bibliography on previous orifice studies.

2.1.2.1 ORIFICE INLET

Injector orifice inlets generally are classified as rounded, chamfered, or sharp-edged. The inlet geometry combined with the orifice bore size must be considered relative to the flow-stream characterization. Inlet geometry can affect the velocity profile, which in turn affects the atomization produced by impinging elements (eqs. (3) and (4) in sec. 2.1.1.1.2). Also, undesirable (unpredictable and unstable) separated flow, partially attached flow, and stream misdirection can be avoided by proper (contoured) orifice inlet geometry, especially when orifices with small L/d values are necessary. The key to acceptable orifice inlets is the reproducibility of the inlets and of the resultant stream, rather than the absolute shape or discharge coefficient C_d. Orifice pressure drops that are relatively high but repeatable are almost always prefereable to those that are relatively low but vary widely.

Well-rounded inlets will prevent cavitation and will provide better flow direction and better flow control, thereby avoiding free-stream jet breakup; these benefits are particularly true for an orifice with relatively low L/d value in comparison with the sharp-edged orifice. Also, rounded inlets, chamfered inlets, and converging orifices (orifice inlet larger than orifice exit) are more prone to full flow and produce higher C_d's than sharp-edged orifices. The C_d of rounded or chamfered inlets changes rapidly with inlet radius-to-orifice diameter ratio R/d or chamfer-to-orifice diameter ratio Ch/d if the curvature or the chamfer is very small. Figure 13 (adptd. from ref. 72) shows the approximate variation of C_d (based on major bore diameter d) for variations in uniform inlet radius R, uniform re-entrant burr B_{re}, and uniform inward burr B_{in} for a full-flowing orifice of L/d = 3 with zero cross velocity at a Reynolds number in the fully turbulent region. Small variations in inlet curvature R produce significant changes in C_d and nonreproducible pressure drops when the injector operates in the steepest portion of the R/d curve. It was found that five orifices of identical design with rounded inlets produced significantly different results during water flow tests (ref. 73). Other studies have shown that reproducible results could be obtained from rounded entrances only when the inlets were highly polished. If a chamfer is assumed to be about

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*Detachment of the jet from the orifice wall.

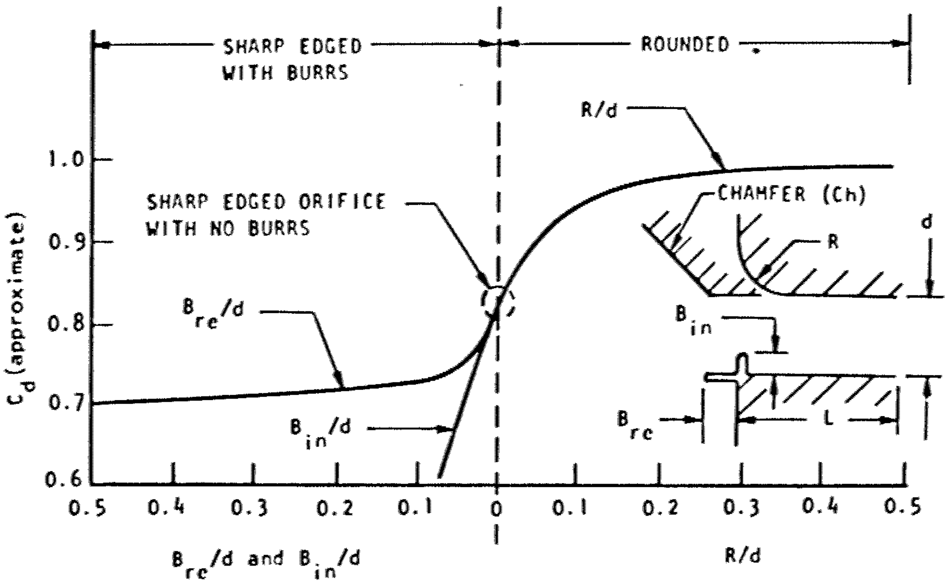


Figure 13. – Discharge coefficient as a function of orifice inlet geometry (adptd. from ref. 72).

half as effective as a rounded entrance, a value for Ch/d of 1.2 would be equivalent to a rounded inlet R/d of 0.05 and would result in large variations in both C_d and pressure drop for small changes in Ch. Changing the orifices to contain sharp entrances in this sensitive range reduces the potential C_d variations.

In actual injector hardware, rounded inlets, large chamfers, and sharp edges have all worked satisfactorily. However, with sharp-edged inlets, the control of burrs has been extremely difficult. A small burr, as shown in figure 13, produces a sizable drop in C_d. Drilling from the injector face (orifice outlet) almost always produces orifice inlet burrs, and removing these burrs while still maintaining a sharp and reproducible orifice inlet has been extremely difficult. In the Apollo Service Propulsion System study (refs. 69, 70, and 71) variations in C_d between sharp-edged orifices in the as-drilled condition and in the lapped condition reached 15 percent. Drilling from the inlet side of the injector orifice has reduced the entrance burr but has resulted in the deburring problem being transferred to the orifice exit, where burr removal can disturb the exiting stream and result in overheating of the chamber wall and reduced performance (sec. 2.1.2.3). In general, however, inlet burrs have been much more troublesome than exit burrs.

Orifice inlets can be divided into three types for fabrication purposes: accessible, semiblind, and blind. Accessible inlets are inlets in which direct access to the orifice entry from behind is possible after orifice fabrication. Self-impinging orifices drilled into rings before the rings are brazed into the injector (F-1, Thor, Atlas, Jupiter, and H-1) have completely accessible inlets. After installation of the rings, however, they may become blind inlets. The semiblind inlet is an orifice inlet that is accessible from the side but not directly from behind. The oxidizer orifices supplied by the radial feeder passages in the center of the J-2 injector are semiblind, as are the fuel orifices of the H-1 gas-generator injector and the Atlas vernier-motor injector. The blind inlet is one in which there is no direct physical access to the inlet side of the orifice. Orifices drilled into integrally cast ring manifold bodies (Lance) have blind inlets, as do orifices drilled after rings are welded into the body (LEM ascent engine).

Completely accessible sharp-edged inlets, drilled from the outlet side, are commonly used; they are successfully deburred by polishing, rodding, and repolishing, but consistency of orifice flow characteristics depends on operator skill. The F-1 injector has large ($\approx$ 0.250 in.) sharp-edged orifices in copper rings, which are drilled (before ring installation) from the outlet side and are then machined on the entrance side for proper ring thickness. Burrs from the machining are removed by hand, and acceptable inlet control on these relatively large orifices is obtained in spite of the deburring variations.

Rounded inlets for completely accessible orifices, either of the recessed or of the flush type, have been used successfully in production injectors. Accessible oxidizer orifice inlets on the J-2 are made with a contoured mechanical cutter. Drilling and chamfering with relatively small Ch/d values (1.3 to 1.4) has been successful with fully accessible orifices in Atlas-type injectors, but this practice can be used only when relatively high ΔP tolerances are allowed. Orifice inlets with small Ch/d chamfers could be replaced with sharp-edged orifices to achieve acceptable ΔP's. Both ECM and EDM processes have been used to drill (machine) completely accessible orifices and produce acceptable inlets.

Semiblind inlets, with radial-passage accessibility, normally are drilled from the outlet side and are then deburred at the inlet by polishing along the radial, inserting a rod, if necessary, to push out the inward projecting burr caused by the polishing, and again deburring by polishing. Results are highly dependent on the individual doing the deburring. Both electropolishing and vapor honing have been used to minimize inlet burrs and to produce a more uniform orifice entrance. Semiblind inlets have been satisfactory in injectors even without deburring when the orifices were very carefully drilled, but only when the allowable injector ΔP tolerance was large (up to $\pm$ 25 percent).

In general, completely blind inlets do not have acceptable pressure-drop control when normal mechanical drilling techniques are used. Underdrilling and then reaming, or step drilling, has been partially acceptable, but the orifice inlet geometry is not always adequately controlled. Drilling and then alkaline etching has been successful in controlling orifice inlets in blind-orifice aluminum injectors. Control of injector ΔP within $\pm$ 8 percent was achieved with the blind-orifice LEM ascent injector because of the repeatable entrances achieved through the EDM process with rotating electrode. Drilling into either salt or a low-melting-point alloy reduces the burr problem, but complete removal of the low-melting-point alloy without damaging the injector is troublesome and sometimes impossible.

Modification or repair of existing injectors with blind inlets often results in orifice characteristics that are not the same as those of the original orifices. Overdrilling existing orifices or drilling new orifices from the outlet side can result in orifice inlet burrs. Operational characteristics of such modified injectors may be significantly different from the characteristics of the original injector if burr removal and orifice entrance geometry are different. Orifice modification techniques that are identical to the initial orifice installation method (e.g., orifices EDM'd from the face) can produce excellent and reproducible results.

2.1.2.2 ORIFICE BORE

The orifice bore dimensions such as the bore length, diameter (width for annular shapes), surface finish, and angle are key controlling features of the orifice. Improper orifice bore designs can result in (1) unstable or unpredictable flow, with concurrent performance or thrust dropoff, (2) misimpinging or poor quality streams that result in performance losses, or (3) misdirected streams that produce overheating.

The hydraulic-flip phenomenon (i.e., detachment of the jet from the orifice wall) leading to unstable or unpredictable flow is normally and most easily controlled by the orifice L/d parameter. Reference 74 presents an equation using the L/d parameter for predicting the injector pressure drop at which a full-flowing orifice will separate when flowing into air at 1 atmosphere. Another investigation (ref. 75) showed that the particular gas used as the back pressurant also significantly affects the hydraulic-flip point, so the separated-flow equation (ref. 74) should be used only as a first estimate. Also, the cross velocity drastically affects the hydraulic-flip point (ref. 75). Chamfering or rounding the orifice inlet reduces or eliminates the separated-flow region and reduces the effect of cross velocity on the hydraulic-flip point.

When normally-full-flowing orifices exhibit separated flow under cold-flow test conditions with 1-atmosphere back pressure, neither the cold-flow injector pressure drop nor the element mixing and atomization characteristics are meaningful. Both water and gaseous back pressure have been used successfully to force full flow during cold-flow testing. Air flow was used successfully on the J-2 concentric-tube injector to cold calibrate each individual oxidizer and fuel orifice. Reducing the orifice flowrate until full flow was achieved, even with only 1-atmosphere back pressure, has resulted in excellent correlation with full-flow, hot-firing C_d values.

The Apollo Service Propulsion System study (refs. 69 through 71) showed that stream direction control is very poor with orifices having low L/d values. Orifice L/d's of about 4 were required to produce streams concentric with the orifice centerline, even with zero cross velocity.

Correlation of the hydraulic-flip point with propellant cavitation characteristics under limited conditions has been attempted in several studies (refs. 69, 70, 71, 76, and 77). No general correlation that will account for the orifice and flow variables normally encountered in injectors has been established, but hydraulic-flip characteristics of a propellant have been demonstrated by means of an easily handled cold-flow fluid with a boiling point different from that of the propellant.

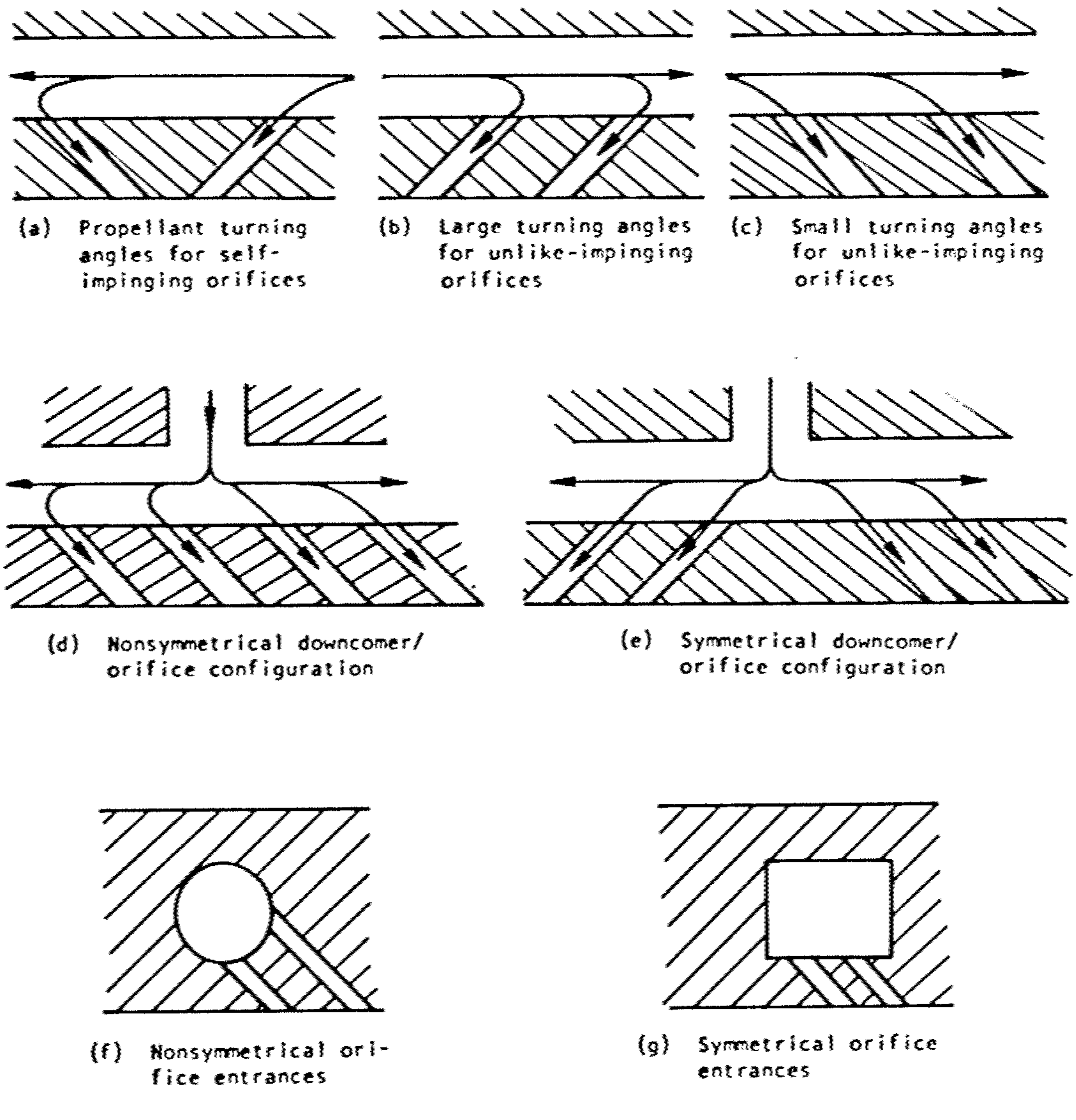
The Apollo Service Propulsion System study and other programs have shown the importance (relative to atomization and mixing) of the orifice orientation in relation to the propellant cross-velocity direction (fig. 14). Orifices oriented as in figure 14(a) (as in many self-impinging orifices in ring-type injectors) have a significantly higher flow through the orifice with the lower fluid turning angle. Orifices oriented as in figure 14(b) have reasonably consistent flow characteristics (if the cross velocity is kept constant through the use of tapered ring manifolds), as do the orifices of figure 14(c), but the characteristics of each set are different. With orifices arranged as in figure 14(d), the flow characteristics of the orifices to the right of the downcomer are different from those of the ones to the left; an arrangement as shown in figure 14(e) avoids this problem. The configuration of figure 14(f) results in different flowrates to the two orifices, whereas the configuration of figure 14(g) results in the same flowrates. The effect of cross velocity on orifice C_d is reduced considerably by using a large inlet contour, chamfer, or counterbore.

The C_d of a fully flowing sharp-edged orifice varies with the L/d of the orifice, as shown in figure 15, but becomes constant at an L/d of around 3. Gradual decrease in C_d at higher L/d values as a result of friction is not significant for orifice L/d's normally used in injectors. For micro-orifices and for annular orifices (concentric-tube type), frictional pressure drop can be significant, and thus a high degree of control on the surface finish is required.

Rectangular and square orifice bores have been used, both for improved fabricability and for better mixing characteristics. The flow characteristics of noncircular orifices have been studied by several investigators (refs. 5 and 78 through 82). Reference 83 is a review of the literature on pressure drop in noncircular ducts and annuli.

Orifice plugging can result in orifice stream misdirection and subsequent wall streaking (overheating). Water (condensed combustion product) will tend to remain in small orifices ($<$ 0.1 in. diam.). During chilldown on start, the water can freeze and block the orifice flow. Complex purge techniques may be required to prevent this problem.

Contaminants in the feed system such as machining chips, O-ring fragments, solid combustion products (from the propellants, hypergolic igniters, or solid-propellant turbine



(a) Propellant turning angles for self-impinging orifices

(b) Large turning angles for unlike-impinging orifices

(c) Small turning angles for unlike-impinging orifices

(d) Nonsymmetrical downcomer/orifice configuration

(e) Symmetrical downcomer/orifice configuration

(f) Nonsymmetrical orifice entrances

(g) Symmetrical orifice entrances

Figure 14. – Various types of orifice orientations.

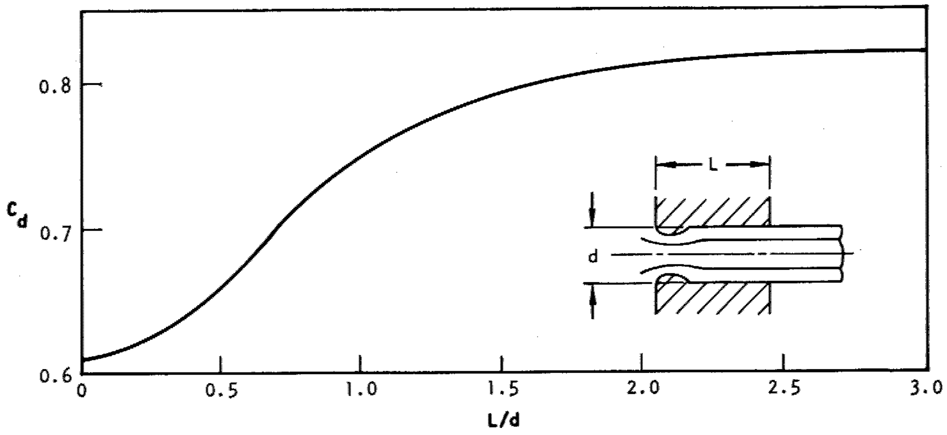


Figure 15. – Discharge coefficient vs L/d for a square-edged short tube flowing full (ref. 72).

starters), and lubricants have plugged injector orifices. Orifices less than about 0.020 in. in diameter or width have been particularly subject to plugging, and an absolute lower limit of approximately 0.015 in. has been decreed in some cases.

2.1.2.3 ORIFICE OUTLET

Improper injector outlet geometry has a negative effect on the stream flow characteristics. Stream misdirection has been caused by a very shallow angle between the orifice and the injector face, by a nonuniform orifice outlet geometry, and by a burr at the orifice outlet. Misdirection and subsequent misimpingement have produced a decrease in performance as well as chamber wall streaking and overheating. Poor outlet concentricity of the concentric-tube injector element also has led to wall streaking and overheating.

Flow-stream direction is influenced by nonsymmetrical drill breakthrough when the orifice is drilled from the inlet side. Misdirection caused by a shallow exit angle or nonsymmetrical breakthrough has been avoided by local grooving or spotfacing to increase the effective angle. Also, the orifice outlet geometry has been more closely controlled for orifices drilled from the injector face when flats are machined normal to the surface before drilling or when drill bushings are used.

Deburring sometimes results in stream characteristics worse than those produced by the burrs, usually by producing inward pointing burrs or nonuniformly rounded outlets. Multiple-pass drilling, step drilling, drilling and broaching, and EDM are satisfactory for drilling from the orifice inlet side. Drilling from the orifice exit side usually does not result in deleterious burrs on the orifice exit, except for very soft materials such as copper.

Concentric-tube concentricity generally is maintained by mechanical centering devices or ribs.

2.1.2.4 ORIFICE TOLERANCES

Injector orifice tolerances are required in order to avoid problems such as (1) misimpingement or maldistribution, with subsequent performance loss, (2) stream misdirection and overheating, (3) failure to achieve the design operating level, and (4) combustion instability. Orifice tolerances usually are specified along with the physical orifice dimensions (bore diameter, inlet radius, etc.), although a flowrate vs pressure-drop tolerance sometimes is used in addition to the dimensional tolerance.

Some injectors have no ΔP tolerance requirements, others have an overall ΔP tolerance requirement, and some require individual orifice ΔP measurements. Small injectors with few elements sometimes have high rejection rates unless extreme care is taken with each orifice. Large injectors with many orifices need not and cannot be kept within a tight tolerance and, therefore, it has been necessary to allow a wider tolerance on some of the orifices (10 percent of the orifices, for example, for the LEM ascent injector). The overall ΔP tolerance is still maintained with the relaxed tolerances. On the J-2 injector, tighter control is maintained on those elements next to the wall that can result in wall streaking than on the remainder of the elements.

Standard drills have a diameter tolerance too wide for many injector ΔP requirements. Standard drills have been used successfully by selecting only those within a tight tolerance, such as $\pm$ 0.0002 in. for small orifices with tight ΔP control or + 0.003/−0.002 in. for the F-1 orifices ($\approx$ 0.250 in. diam.) with looser ΔP control. Standard drills are adequate even without drill selection for very high ΔP allowances.

Even with properly controlled individual orifice characteristics, local element atomization and mixture-ratio distribution have been drastically disturbed by failure of opposed-element streams to intersect properly (ref. 54). The absolute location of the impingement point of two or more streams usually is precisely located on the blueprint, but in general a slight variation of this spatial point has little or no effect on combustion-oriented characteristics. A slight misalignment of the individual orifice centerline, however, can result in wall streaks or lower performance and may also affect combustion stability, particularly for near-wall elements. Experimental results with orifice diameters of 0.073 in. and 0.052 in. resulted in a c^* loss (IRFNA-UDMH propellants) of slightly more than 2 percent when the stream centerlines of the opposed-doublet element were deliberately mismatched by 0.010 in., all in one direction (ref. 44). Also, centerline misimpingement can change secondary mixing characteristics. The use of drill bushings, with all of the element orifices located within a single bushing, has reduced centerline misimpingement problems significantly when the bushing was not moved between drilling operations.

Better orifice reproducibility has been achieved with rotating EDM electrodes than with the nonrotating ones. Drill drift, drill breakage, orifice geometry variation at the drill inlet, and orifice diameter tolerance have been reduced considerably by the use of drill bushings and automatic speed- and torque-controlled drilling machines, especially for small orifices.

2.1.3 Flow-System Geometry Upstream of the Orifices

Local variations in injector mixture ratio and mass flow caused by deviations from the predicted orifice inlet conditions frequently have resulted in problems in performance, stability, and durability. Deviations in orifice-inlet conditions can be caused by design deficiencies or fabrication inadequacies in any portion of the feed system upstream of the orifices (e.g., in the ring grooves, downcomers, radial and transverse passages, or dome and ring manifolds). Failures such as wall overheating can be caused by deficiencies in any single upstream flow-system component and by the element configuration or individual orifice characteristics; therefore, the specific cause of any such deficiency often is extremely difficult to determine. Detailed system cold-flow studies frequently have been required in order to avoid potential problem areas that can cause a flow discrepancy.

Deviations in individual orifice flow from that predicted have three primary causes: unpredictable orifice flow characteristics under known inlet conditions (sec. 2.1.2), unpredictable orifice inlet static pressure, and unpredictable orifice inlet cross velocity. The primary purpose of the flow-system geometry upstream of the orifices is to produce uniform static-pressure and cross-velocity conditions upstream of the orifice inlets. Flow-system geometry requirements upstream of the orifice will vary with the element type and orientation, however. A high cross velocity can result in drastically different flowrates to each differently oriented orifice. Low cross velocities are highly desirable for all element patterns. New element patterns introduced into existing injector bodies that are reasonably well optimized for an existing element pattern can produce disappointing results because of unsatisfactory upstream flow conditions.

An orifice inlet static pressure that is higher than the predicted value is produced primarily by direct impingement of high-velocity flow on a flow passage entrance or orifice entrance or by flow stagnation at the end of a passage. Low static pressure is produced primarily by high-velocity flow across the entrance to a flow passage or orifice or by excessive stagnation pressure losses somewhere upstream. Standard references (e.g., ref. 84) generally are used to calculate total-pressure and static-pressure profiles in various passage configurations.

2.1.3.1 RING GROOVES

Ring grooves are continuous annular manifold passages, usually located directly behind the injector face. Variation in the orifice flowrate due to high and low static pressure and high cross velocities is a common problem with ring injectors. These variations can create problems in performance, stability, and durability. Figure 16 qualitatively shows the variation of total pressure, static pressure, and cross velocity normally produced in a constant-area ring groove near a propellant inlet. Original stagnation pressure is produced immediately underneath the propellant inlet, with the total pressure decreasing as a result of turning losses, then slowly diminishing along the ring because of friction drop. Static pressure is highest immediately underneath the propellant inlet, but decreases rapidly because of the increased velocity resulting from the reduced effective flow area. Static pressure increases as full flow is established, then slowly rises to total pressure at the end of

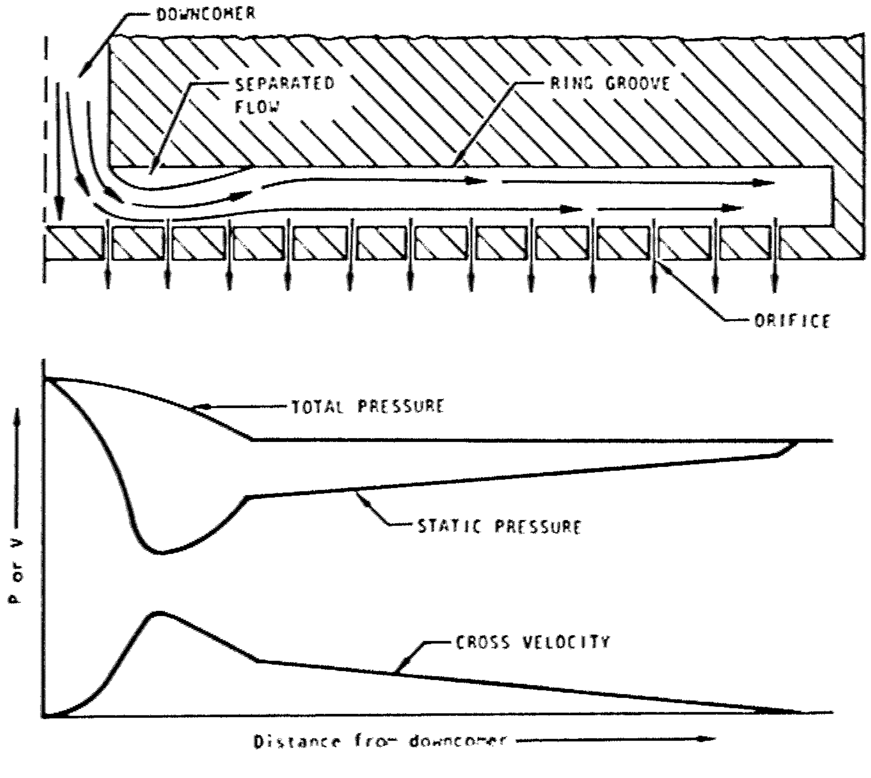


Figure 16. – Variation of pressure and velocity in a constant-area ring groove.

the ring groove as the ring groove velocity decreases with successive mass loss through the orifices. Cross velocity is zero directly underneath the propellant inlet, increases to a high value in the region of detached flow in the ring groove, then slowly decreases to zero at the end of the ring.

In addition to the variations in pressure along the ring groove, there are absolute pressure-level differences between rings caused by differences in the propellant inlets and in the flow system upstream of the propellant inlets. Orifice flowrates will be lower in the low-static-pressure region because of the higher cross velocity as well as the reduced inlet pressure. An example of pressure variations and consequent flow variations in a ring groove (F-1 gas generator injector) is given in reference 85.

Tapered ring grooves or rings with large flow area may reduce the static pressure variation in the full-flow region, but do not eliminate it at the end of the ring groove or at stagnation points between inlets. Major reductions in ring-groove pressure and velocity variations have been accomplished by controlling downcomer geometry (sec. 2.1.3.2).

Placement of combustion stability baffles directly downstream of the ring inlet (downcomer) flow has eliminated the largest flow deviations. Local deflector plates downstream of the inlet have been used to reduce the maximum ring groove pressure. When elements are located more than one propellant-inlet diameter from the propellant-inlet centerline, most of the static pressure increase at the orifice inlets due to direct flow impingement is avoided.

The most successful but complex device for producing uniform static pressure and cross velocities has been the distribution ring (fig. 17). A variable ΔP across the distribution ring is produced by the use of different-sized distribution ports to compensate for the variation in static pressure and cross velocity within the main ring-groove flow passage. With only a few orifices fed from each distribution-ring port, as shown in figure 18, variations in static pressure and cross velocity at the orifice inlets are reduced significantly. More nearly uniform results are obtained when the distribution ring ports are not positioned in line with either the downcomer or the ring orifices.

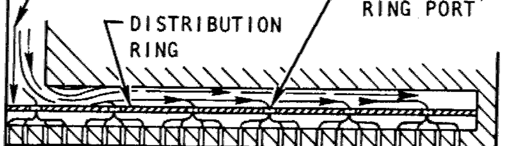


Figure 17. – Sketch of cross section of a distribution ring.

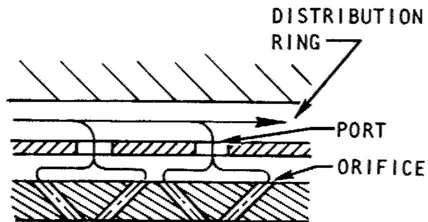


Figure 18. – Relation of distribution-ring ports to orifice entrances.

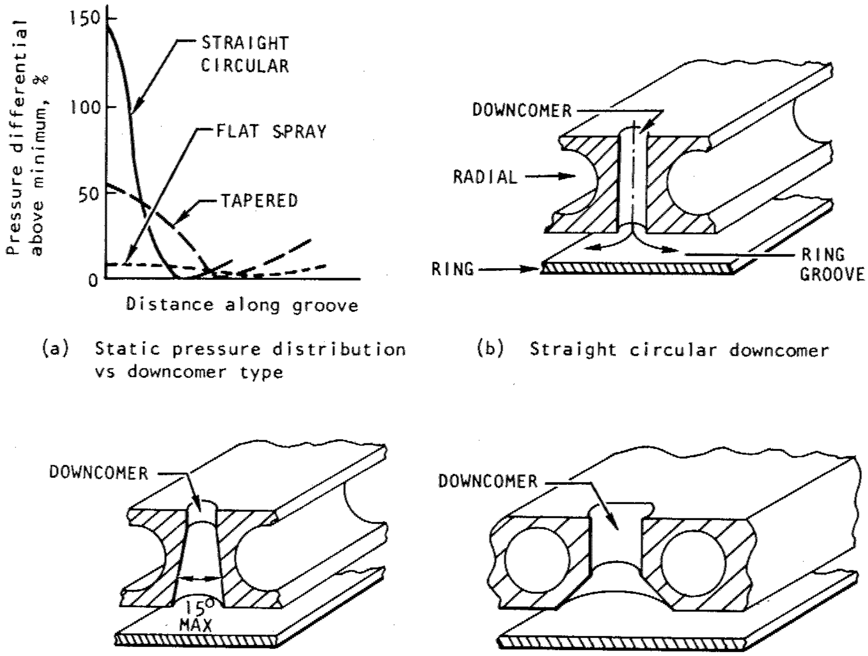
2.1.3.2 DOWNCOMERS

Downcomers are passages that feed the propellant from the rear of the injector to the ring grooves or injector orifices. These axial feed passages have been a major cause of static-pressure variation in ring grooves. The downcomer velocity head acting on the upstream (orifice inlet) side of the ring results in a high static pressure and consequent variations in orifice flow directly underneath the downcomer. Low velocities at the downcomer exit virtually eliminate the velocity head, but injector body geometry limitations usually dictate the relatively small downcomers that produce high velocities.

Figure 19(a) shows the static pressure distribution on the ring upstream (back) surface produced by three downcomer configurations from large (open) manifolds for the F-1 injector (figs. 19(b)-(d)). The simple straight circular downcomer of figure 19(b) produced a very high velocity and, theoretically, would cause a flowrate about 60 percent higher for an orifice located directly downstream of the downcomer, in comparison with one in the minimum static pressure region. The tapered downcomer of figure 19(c) resulted in a lowered exit velocity and reduced the pressure variation on the ring back surface. Tapering is effective only up to a total taper angle of about 15°, above which stream separation from the wall occurs. The "flat spray" configuration of figure 19(d) forces the flow sideways and allows the use of a much larger taper angle and resulting lower exit velocity. The maximum spread in orifice flowrate was reduced to about 3 percent with this configuration.

Downcomers from radial and transverse manifolds have been troublesome because of the inaccessibility of the downcome inlet and the resultant flow inconsistency from burrs. The straight circular downcomer of figure 20(a) produces a high velocity and essentially the same poor pressure distribution on the ring backside as that of figure 19(b). Slotting and tapering has reduced the downcomer exit velocity. Steeper taper angles can be used without stream separation when a narrow slot with length/width ratios of four or more is used (fig. 20(b)). Improved results have been obtained with the drilled and tapered downcomer design of figure 20(c), which reduced the mass flow in the central portion of the downcoming stream and increased it in the region next to the tapered outer walls. Downcomers as wide as the ring groove or even wider also have been used as a method of reducing the downcomer exit velocities.

Actual flowrate through a downcomer and thus through the downstream orifices is significantly affected by the downcomer inlet geometry. Sharp-edged entrances have



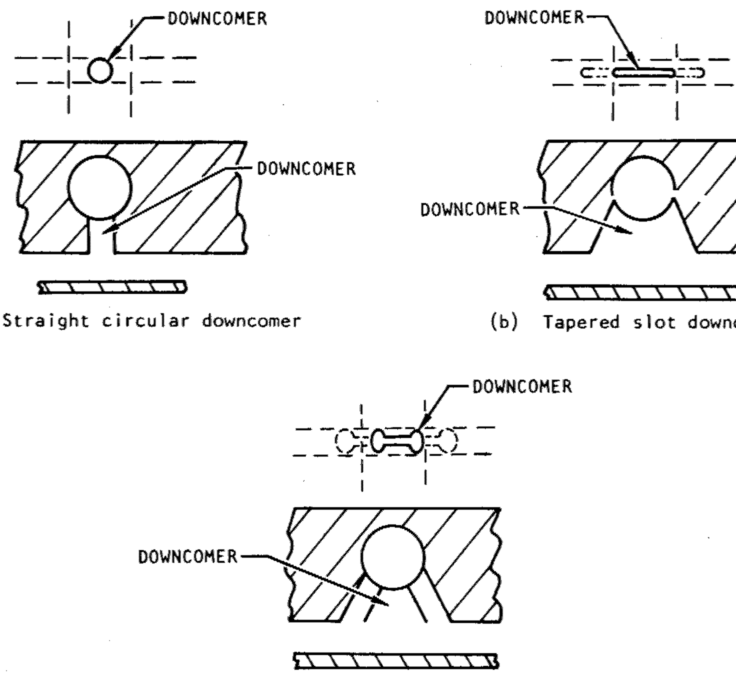
(a) Static pressure distribution vs downcomer type

(b) Straight circular downcomer

(c) Tapered downcomer

(d) Flat-spray downcomer

Figure 19. – Relation of downcomer configuration (open manifold) to static pressure distribution on back surface of distribution ring.



(a) Straight circular downcomer

(b) Tapered slot downcomer

(c) Drilled and tapered slot downcomer

Figure 20. – Three configurations for downcomers from a radial manifold.

resulted in the most reproducible flowrates and highest pressure losses, followed by wide chamfered entrances, and finally by contoured entrances. The problem of burrs is not so critical with downcomers, because of their relatively large diameters in comparison with the burr dimensions. A reduced diameter at the downcomer inlet can be used where high pressure drop within a downcomer is required for system balance, but a low downcomer exit velocity is still desired.

Downcomers sometimes are used to manifold propellants directly to the injector orifices; i.e., no ring grooves are used. Performance losses with some injectors were suspected of being due to stream misdirection caused by poor (nonuniform) alignment of the downcomer centerline with the orifice centerline (refs. 86 and 87). Cold-flow studies and hot-firing tests proved that the lower performance was related to increased downcomer misalignment.

2.1.3.3 DOME MANIFOLDS

Dome manifolds (manifolds that span the back of the injector) can produce flow maldistribution to rings and to individual orifices as a result of static-pressure and velocity gradients within the dome. Flow maldistribution in domes often results from the relatively high inlet velocities normally utilized to keep the propellant inlet line small. This high-inlet-velocity problem has been severe with large injectors but normally is not too troublesome with small injectors. Figure 21 presents four configurations that improve flow distribution in a dome manifold.

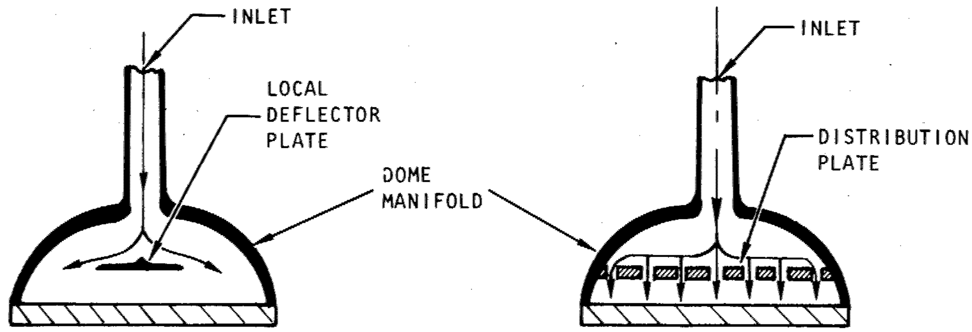
High pressures have been produced under the inlet of domes with single axial inlets. Local head suppression devices such as deflector plates (fig. 21(a)) and distribution plates (fig. 21(b)) have been effective in reducing this velocity-head overpressure.

Domes with side inlets or nonaxial back inlets can be even more troublesome because of the nonsymmetrical flow produced in the dome. The nonuniform flow conditions produced by a large nonsymmetrical back inlet can be reduced considerably by using the distribution plate shown in figure 21(c). A ring manifold with two side inlets and a distribution ring (fig. 21(d)) was effective in producing uniform dome manifold conditions with small overall propellant manifolding volumes, as was a single tangential inlet ring manifold with a distribution ring and a tapered manifold.

The reduced flowrate through dome outlets resulting from a high-velocity jet flowing directly across the outlets (fig. 22(a)) was alleviated considerably by moving the dome inlet line farther from the outlets (fig. 22(b)).

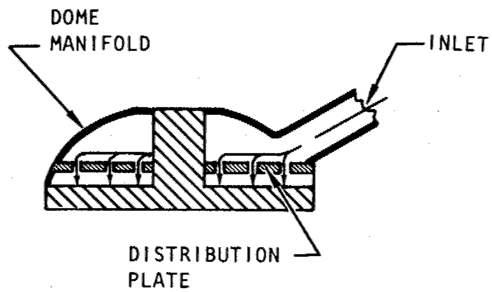
2.1.3.4 RING MANIFOLDS

Ring manifolds (annular manifolds) closely resemble ring grooves (sec. 2.1.3.1) hydraulically and suffer from the same general problems. A variation in the static pressure and cross

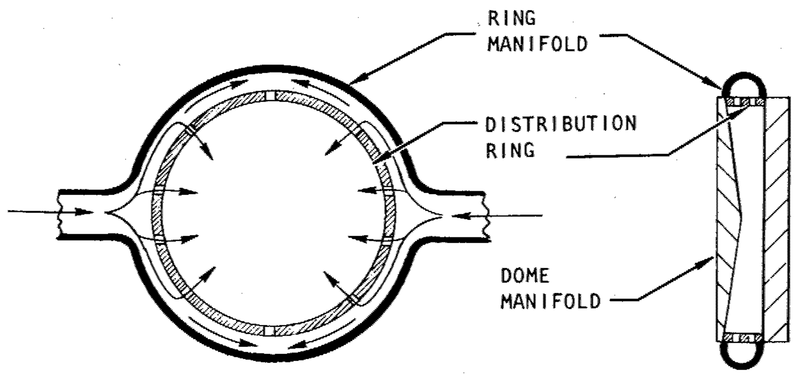


(a) Dome inlet with local deflector plate

(b) Dome inlet with distribution plate



(c) Non-axial dome inlet with distribution plate



(d) Dome manifold fed from ring manifold with distribution ring

Figure 21. – Four configurations for obtaining improved flow distribution in dome manifold.

(a) High jet velocity across dome manifold outlet

(b) Decreased jet velocity across dome manifold outlet

Figure 22. – Effect of position of dome inlet line on outlet flowrate.

velocity at the inlet to the radial and transverse passages (ring manifold outlets) will produce variations in radial and transverse passage flowrates and eventually in orifice flowrates. Low inlet velocities are the best means of reducing the potential maldistribution, but often, particularly in large injectors, the velocity cannot be reduced sufficiently to eliminate the problem.

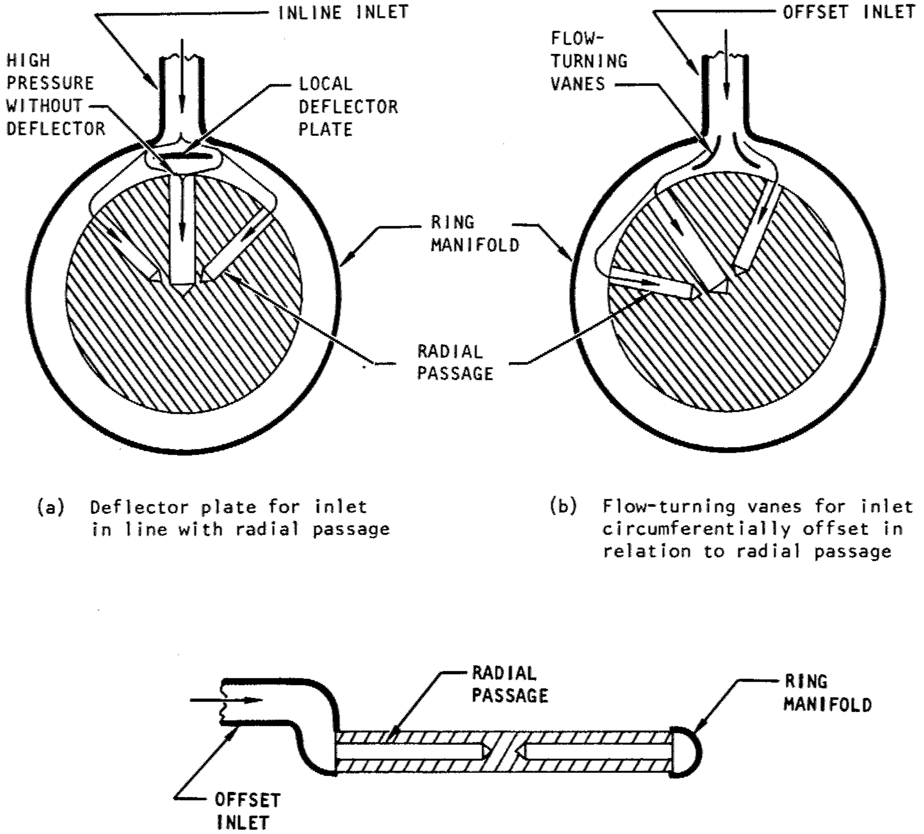
Static-pressure maldistribution caused by direct impingement can be reduced by local deflector plates (fig. 23(a)), flow-turning vanes (fig. 23(b)), offset inlets (figs. 23(b) and (c)), and tangential inlets.

Tapered ring manifolds have been effective in keeping static pressure and cross velocities reasonably constant within the manifold except near the inlets. For long high-velocity flow paths around the ring manifolds, both friction losses and contour losses can be significant and must be included in the pressure-distribution calculations.

Distribution rings with variable ports or with variable gaps, preferably offset from the radial inlets, have been successful in producing more uniform conditions at the radial inlets.

2.1.3.5 RADIAL AND TRANSVERSE PASSAGES

Radial and transverse passages are injector manifold passages that are normal to the flow direction in the injector orifices (combustion chamber). These passages supply propellants to the downcomers or to the primary injection orifices. Improper design of radial and transverse passages can result in variation of static pressure and cross velocity at the manifold outlet ports and subsequent maldistribution of flow through the downstream



(a) Deflector plate for inlet in line with radial passage

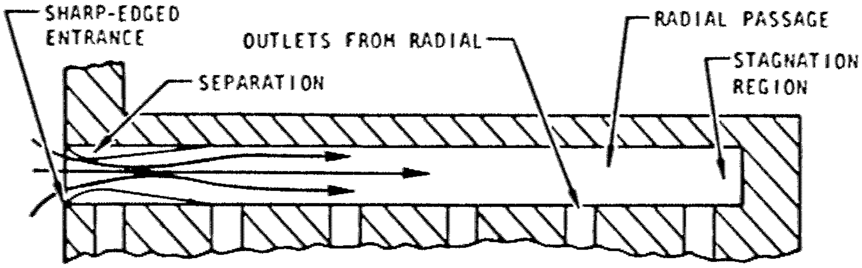
(b) Flow-turning vanes for inlet circumferentially offset in relation to radial passage

(c) Inlet axially offset in relation to radial passage

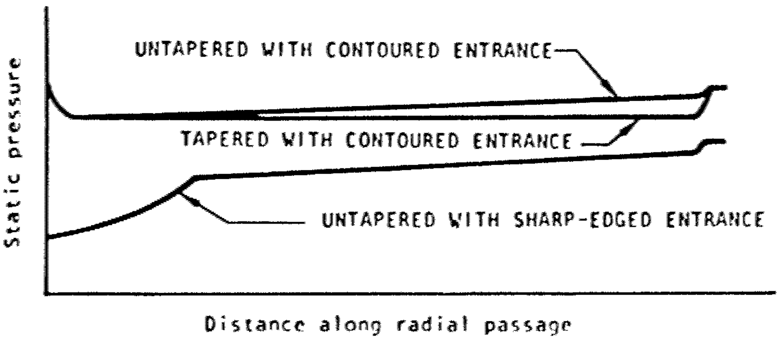
Figure 23. – Three configurations for improved pressure distribution in ring manifolds.

orifices. Because of injector volume limitations, the low manifold velocities that would minimize these variations often are unattainable.

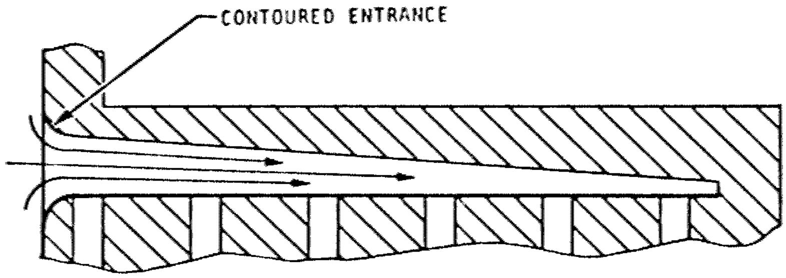
The relation of static-pressure distribution to passage geometry is illustrated in figures 24 and 25. Straight radials with sharp-edged entrances (fig. 24(a)) produce static pressures that are low in the separation region just within the radial, increase slowly along the radial as the flow reattaches to the wall of the passage, and then slowly continue to increase as the fluid velocity decreases as a result of flow branching through the outlet ports (fig. 24(b)). At the end of the radial, the velocity goes to zero and there is a steep pressure rise. Because all



(a) Untapered radial passage with sharp-edged entrance

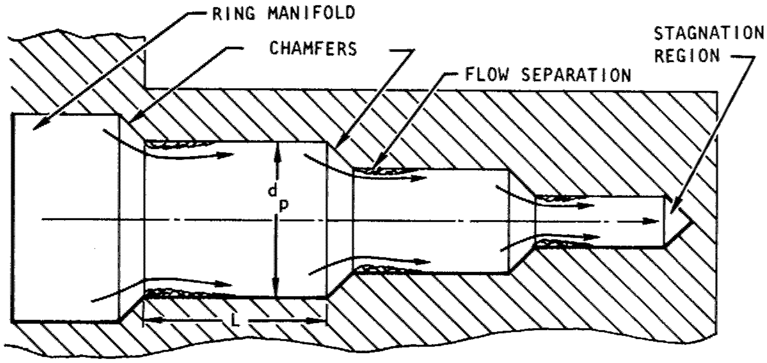


(b) Static pressure along radial passage

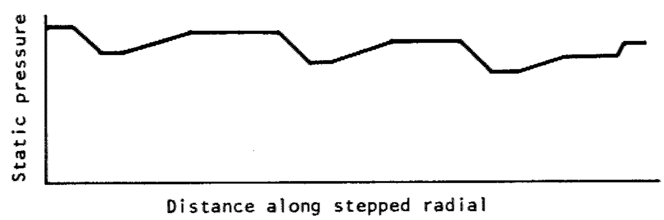


(c) Tapered radial passage with contoured entrance

Figure 24. – Variation of static pressure along tapered and untapered radial passages.



(a) Stepped radial passage with chamfered inlets



(b) Static pressure profile of (a)

Figure 25. – Variation of static pressure along stepped radial passage with chamfered inlets.

fluids lose pressure when entering and flowing along a passage, the total pressure (static pressure plus velocity head) at the end of the manifold will be less than that at the manifold inlet.

Sharp-edged orifices result in the largest total-pressure loss, because of flow contraction and expansion losses in the separated-flow region. Thus contouring or chamfering the inlet to the radial passage results in a larger static pressure immediately within the entrance (fig. 24(b)) and a smaller total-pressure loss.

Contouring the inlet and tapering the passage (fig. 24(c)) results in a relatively uniform static pressure and velocity along the radial (neglecting friction losses) until near the end of the radial, where there is a static-pressure increase (fig. 24(b)). A step at the end of the radial can be used to create a stagnation-pressure loss equal to the velocity-head recovery and thereby eliminate this pressure rise.

Stepped radials (fig. 25(a)) with the commonly used chamfer at the step produce a stagnation pressure loss at each of the steps, and the static pressure near the end of the radial may be considerably lower than it is in the first portion; in some cases, if the steps are small and the flow diversion through the outlets is high, the pressure will be higher. With low values for L/d_p downstream of each step, there will be a continual pressure increase along any step (fig. 25(b)).

Manifold outlets located in the separated-flow region of either a straight or tapered radial with sharp or chamfered inlet, or in any one of the separated-flow regions of a stepped radial, have a lower inlet pressure and flowrate than one located a short distance downstream. In addition, the pressure distribution in the separated-flow region is sensitive to the inlet or step geometry. Accuracy of prediction improves as the outlet is moved away from the inlet or step. With stepped radials, the best results have been obtained when the outlet was located immediately upstream of each step.

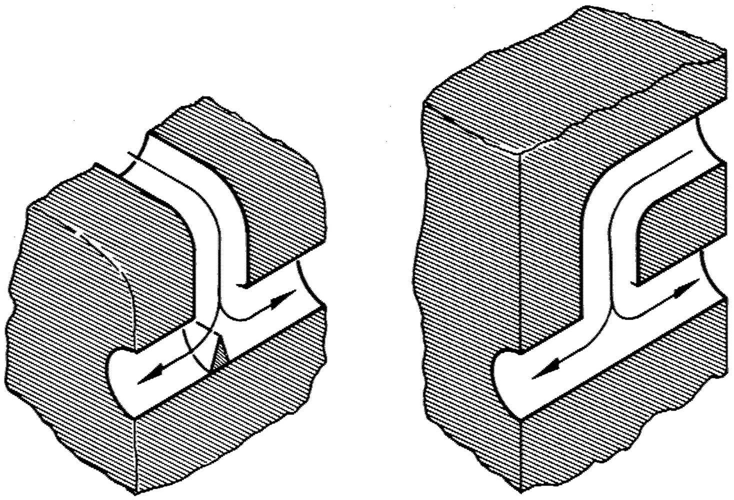
The prediction of flowrate through radial or transverse manifold outlets is difficult under the best of conditions and may be seriously in error, particularly in the case of a sharp-edged manifold entry or a stepped radial or in the event that a large portion of the total manifold flow passes through a single outlet and affects the next outlet downstream. Experimental determination of outlet flowrates under simulated operating conditions often is necessary.

The construction of radial and transverse passages for the gaseous fuel used with concentric-tube injectors (with fuel in the outer annulus) has been somewhat different from that of the radial or transverse passages for ring-type injectors. In these designs, the central oxidizer tubes or posts simply form a forest through the body of the injector, around which the gaseous fuel flows radially inward and eventually through annular orifices around the posts. The circumferential dimension between the posts is governed by the element arrangement and spacing. The flow area, then, may be adjusted by selecting the axial depth of the gaseous fuel manifold and adjusting this depth to produce, as nearly as possible, a uniform static pressure at each of the fuel outlets from the manifold.

2.1.3.6 GENERAL FLOW SYSTEM UPSTREAM OF THE ORIFICES

Inserts, braces, and other structural members within injectors often produce flow maldistributions because they alter the flow-system geometry. Pickup lines for chamber pressure and feedlines for hypergolic-propellant igniters, which are routed through injector feed passages, also produce the same effects. In most cases, these components are added to the injector after the injector flow system and body structure are finalized to the point at which it is extremely difficult to make modifications. Provision for such components during the initial injector feed system and structure design eliminates or greatly reduces the flow maldistributions.

Flow splitters sometimes are used within a feed system to produce an equal or unequal but fixed flow through each of two downstream flow passages. If the feedline immediately upstream of the flow splitter is not symmetrical in relation to the two downstream flow passages, any unequal flow set up by the upstream geometry may be maintained rather than eliminated by the splitter. Nonsymmetrical flow can be avoided by using inlets that are symmetrical with respect to the two legs (fig. 26(a)) rather than nonsymmetrical (fig. 26(b)). Low velocity in the upstream line also will reduce nonsymmetrical flow.



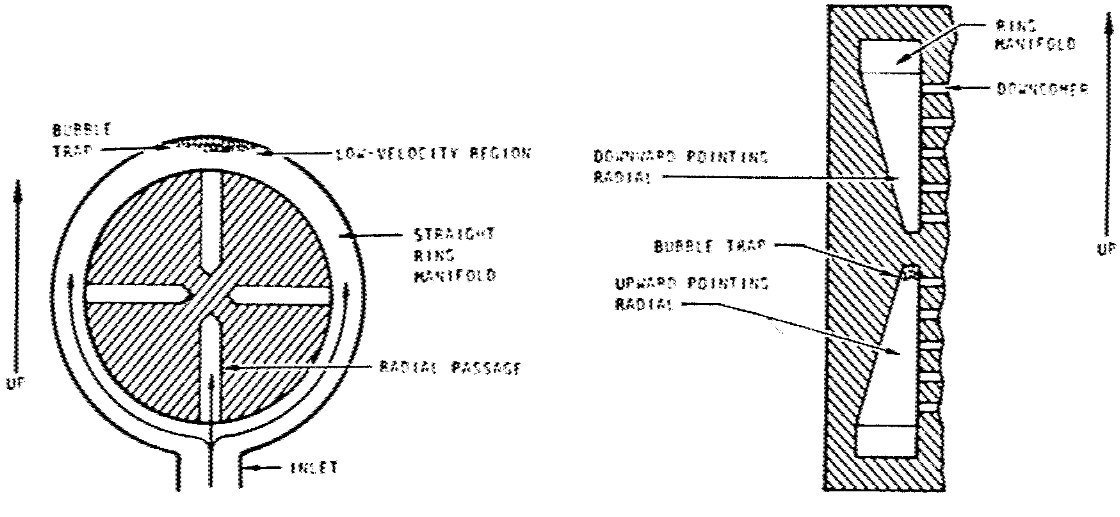
(a) Symmetrical flow inlet with splitter

(b) Nonsymmetrical flow inlet

Figure 26. – Symmetrical and nonsymmetrical flow-passage inlets.

Pressure drop in the feed system greater than pressure drop through the orifices increases the variation in orifice flow for a given variation in the feed system. Fewer problems of this type have occurred when the total pressure drop upstream of the orifices was kept to less than 25 percent of the injector orifice pressure drop. When additional upstream pressure drop must be induced, better results are obtained by employing one restrictor (e.g., an orifice exterior to the injector) rather than several restrictors in parallel within the injector.

Injectors that are positioned so that a bubble trap is formed at very low-velocity regions or at stagnation points (fig. 27) may be subject to hard starts and starting instability. Bubbles trapped in the injector as shown in figure 27(a) were eliminated by increasing the velocity through use of a tapered manifold. Bubbles trapped at the end of an upward-directed radial that projects significantly beyond the last outlet port (fig. 27(b)) can be eliminated by reducing the radial length or by placing the last outlet near the end of the radial.



(a) Bubble trap in low-velocity region

(b) Bubble trap at end of upward-pointing radial passage

Figure 27. – Two kinds of bubble traps in injectors.

2.2 INJECTOR ASSEMBLY

The injector assembly is the structural and material portion of the injector that includes the body, face, domes, manifolds, flanges, baffles, and auxiliary components. Characteristics of the assembly and associated problems are grouped into four major categories: general structure, injector face, baffles and acoustic absorbers, and auxiliary components.

The injector assembly, although not normally flow controlling, can affect flow and consequently degrade performance, stability, and durability. Injector face distortion resulting in misdirected streams and manifold weld failures resulting in propellant maldistribution are examples of assembly-related flow problems. Injector assembly failures can affect the performance, stability, and durability at the time of failure (within milliseconds), or failures can be long term (e.g., rust, corrosion, and fatigue). Problems associated with the injector assembly can be precluded by paying attention to all aspects of the assembly at the early stages of the design.

In injector design, factors such as face material thickness for structural reasons can influence the orifice flow characteristics, body material thickness can effect the injector manifold designs, provisions for seals can influence manifold locations, and so forth. Therefore, the design of the injector assembly is best accomplished in parallel with the design of flow-system geometry, even though the assembly sometimes is considered secondary to the flow system. Frequently, it has been necessary to move repeatedly back and forth between the assembly and the flow-system designs in order to obtain an acceptable balance between the two. The injector-assembly and the flow-system-geometry design steps, if judiciously handled, produce the complete injector package.

2.2.1 General Structure

2.2.1.1 BODY MATERIALS

Material incompatibility with the propellants and with certain atmospheric conditions can degrade the flow stream and injector structure. Normally the propellants are in contact with the injector body materials for only a short time. Consequently, some materials that are not suitable for use in long-term storage with the propellants are perfectly acceptable in injector bodies. Propellant chemical compatibility with various metals is discussed in references 88 and 89. More detailed information may be obtained from the propellant manufacturers' handbooks and from special reports such as those on fluorine (ref. 90), interhalogens (ref. 91), or space-storable propellants (ref. 92).

Corrosion resistance. – Injector bodies of 347 CRES and other stainless steels have been used successfully with practically all propellant combinations (table I). Pure copper bodies have been used extensively, but were limited mostly to research programs and small-production injector programs because of the low strength of pure copper. Various high-strength copper alloys have been utilized where high strength was required along with good conductivity. Copper cannot be used with nitric acid. Aluminum-alloy injector bodies have been extensively and successfully used with most propellant combinations, but corrosion resistance to nitrogen tetroxide, for example, varies significantly with the alloy. Nickel and high-strength nickel alloys such as Inconel X-750 and Inconel 718 have been used successfully. Nickel cannot be used with nitric acid, although nickel-200 has been successfully used with nitrogen tetroxide. The special problems with propellants at elevated temperatures are treated in section 2.2.2.2.

Ductility. – Cryogenic propellants require body materials with good ductility at very low temperature. Stainless steel, copper, aluminum, nickel, and some of the high-strength nickel alloys have good ductility at low temperature. In some Atlas injectors, with liquid oxygen as the oxidizer, 4130 steel is the body material; sufficient ductility is obtained by heat treating the 4130. An electroless nickel plating was used on the 4130 Atlas injector bodies to prevent corrosion. Occasional peeling of this plating allowed corrosion of the body and sometimes resulted in orifice plugging. The peeling was eliminated only by careful control of the plating process.

Flaws. – Flaws or high porosity in the as-received raw material for the injector body can cause rejection of the finished or partially finished injector because of potential interpropellant leakage. Ultrasonic inspection of forged blanks has reduced this problem considerably. Carbon stringers in forgings have resulted in leakage at welded joints in finished injectors. Vacuum-melt materials for injector bodies reduced the occurrence of this problem.

2.2.1.2 WELD JOINTS

Weld joints frequently are used on injectors to form leak-tight and structurally sound connections between component parts. Heavy welds, especially on small injector bodies, can cause body deformation and shrinkage and result in misalignment of flanges, flange holes, manifold shells, and other problems. Finish machining after the heavy welding rather than before is used to reduce these potential distortion problems. Orifices have been distorted and elements misaligned by heavy body welding or local welding near the elements. This kind of problem has been avoided by orifice drilling after welding, by avoiding local welding, or in some cases by electron-beam (EB) welding. Welding of electroformed nickel bodies has been basically unsuccessful because of the internal stresses that result from the electroforming process. Electron-beam welding of 347 CRES generally has been unsuccessful.

2.2.1.3 BRAZE JOINTS

Braze joints, like weld joints, commonly are used to form leak-tight and structurally sound connections between injector component parts. Leakage at injector ring-to-land, baffle-to-baffle, or baffle-to-face joints has triggered combustion instability, caused thrust chamber streaking and injector-face erosion, and damaged baffles. This braze-bond leakage generally arises from thermal stresses in conjunction with porous braze material or braze-material shrinkage. Braze alloy insufficient to create a satisfactory bond often results from slots or holes that terminate at the joint surface and act as triggers to drain the alloy from the joint area, or from burrs that act as wicks and also drain the alloy from the joint area. Many braze joints do not provide accessibility for 100-percent inspection of the joint, so that deficiencies do not become apparent until the injector has been hot fired.

Problems like those described generally can be prevented by proper design that ensures that the joint is not overstressed, can be fabricated as designed, and can be inspected. Fixes in general are difficult. In some cases, realloying is required; in most cases, the joint cannot be repaired.

2.2.1.4 CLOSEOUT PLUGS

Closeout plugs are plugs (generally metal) used to close a passage or hole that provides machining accessibility. Closeout plugs in injectors frequently have leaked; this is particularly true of very small plugs. When oxidizer leaks into a fuel-rich zone, or fuel into an oxidizer zone, severe injector or chamber burnout can result. Brazing or welding of the closeout plugs is satisfactory in most cases; the choice depends primarily on the joint design and the materials used. Blind plugs or plugs located in a region where they could not be inspected or repaired readily have resulted in leakage problems that did not show up until the injector was tested. Machining the passage to avoid the closeout plug entirely has been the best solution where it could be applied.

2.2.1.5 POSTS

Injector posts are the center tubes of concentric-tube injection elements. Injector body deformation and resultant concentric-tube element nonconcentricity can result in wall or baffle streaking. Nonconcentric oxidizer posts often are bent to achieve acceptable concentricity. Short posts when bent sometimes crack at the thread root (fig. 28); the result is interpropellant leakage and perhaps combustion instability. Long posts do not develop cracks as readily when they are adjusted. Increasing the fillet radius at the base of the post reduces stress concentrations during bending. Match-machining after potential distortion, the use of ductile materials, and annealing of the posts only are other techniques used to eliminate post cracking.

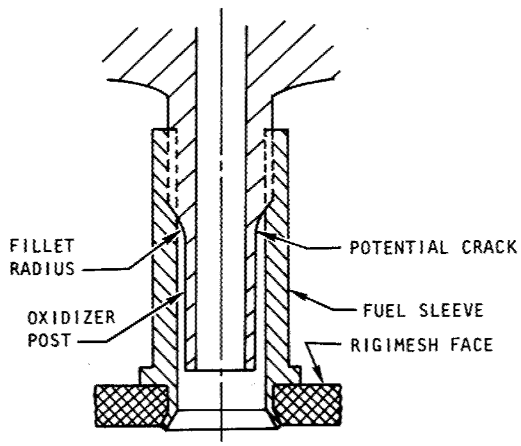


Figure 28. – Potential crack region in concentric-tube post.

Post centering devices often are used to maintain concentricity; however, tolerance buildup on the centering devices and on the elements can result in inadequate concentricity.

2.2.1.6 FACE AND BODY RIGIDITY

Rigidity of the injector face and the complete injector is required in order to avoid detrimental deflections. Cyclic deflection of the injector face, or cyclic "oil canning", can occur if the injector interacts at its natural frequency with the combustion process. In a low-volume oxidizer dome of the Atlas MA-3 injector, removal of the inner dome bolts reduced the injector stiffness and resulted in "buzzing" at about 800 to 1000 Hz. Increasing the stiffness and thus the natural frequency of the injector by reinstalling the inner dome bolts eliminated the problem. Curved-face injectors, optimized for strength and rigidity, have been used successfully in the Titan program.

2.2.1.7 STRUCTURAL SUPPORTS AND FLOW DEVICES

Structural supports and flow devices (e.g., braces, dams, and flow splitters) may become loosened or detached during operation and cause flow variations and orifice stoppage. In some cases, hydraulic ram at startup has broken the attachment between the part and the injector body. In other cases, the attached part has failed in fatigue when fluid flow characteristics caused a flutter or vibration in the part that eventually broke the weld or braze joint. Making the structural support or flow device an integral part of the basic structure has been very successful in eliminating this problem. Design practices that avoid stress concentrations in welded and brazed joints and avoid shapes prone to fail from flutter have also helped.

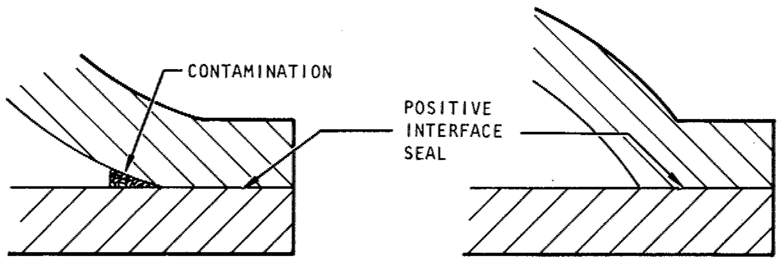
2.2.1.8 CONTAMINATION TRAPS

Cracks and crevices in injector bodies repeatedly have trapped contaminants and led to problems of compatibility, cleaning, and orifice clogging. The contamination trap shown in figure 29(a) was eliminated by redesigning the dome as shown in figure 29(b). Also, drain plugs can be effective in some areas.

2.2.1.9 REMOVAL AND HANDLING PROVISIONS

Removal of injectors from thrust chambers after testing sometimes has resulted in injector or chamber damage because the parts had been jammed together by thermally-induced warpage. The use of screw drivers or hammers to separate the hardware has resulted in scratched sealing surfaces, bent flanges, and dished faces. The use of jackscrew techniques has greatly reduced this type of damage.

Both injector-face and baffle orifices have been damaged by improperly placing the injector face down on hard surfaces or by other improper handling techniques. Attempts to



(a) Contamination trap

(b) Contamination trap eliminated

Figure 29. – Design change to eliminate contamination trap in injector dome manifold.

eliminate this type of damage by tighter handling control have been only partially successful. Some techniques that have been effective are (1) handling in the "face-up only" position (large F-1 injector), (2) using standoff buttons on the face or baffles, (3) recessing the face, and (4) developing special handling instructions tailored to the particular injector.

Injectors frequently have been damaged during transportation as a result of improperly designed shipping containers. Fittings or projections have been bent when the injector weight was supported improperly. Also, container surface materials that contacted relatively soft injector surfaces have nicked and scratched the injector, and loose packing material has plugged orifices. Shipping containers designed as part of the overall injector design have in general been successful in reducing injector shipping damage.

Occasionally damage has resulted from foreign material contamination in the injector. The foreign material may plug the flow passages (or orifices) or it may react with the propellants. Proper cleaning and packaging (bagging) have been successful in eliminating this problem.

2.2.2 Injector Face

The injector face is the portion of the injector that houses the element pattern and usually forms the closed end of the combution chamber. The face of the injector may be subjected to attack by corrosive propellants, combustion products, and the atmosphere; in addition, it may be subjected to severe thermal strains and sometimes large mechanical loads. High temperature of the metal face in contact with the propellants considerably increases the likelihood of chemical attack. A large proportion of injector structural failures has been associated with the injector face.

2.2.2.1 FACE TYPES

Various types of injector faces have been utilized (table I). Most large injectors using oxygen-alcohol or oxygen-hydrocarbon (e.g., Atlas, F-1) and some of the medium-size injectors (LEM ascent) are of the ring-type construction; i.e., the faces are constructed from a series of concentric rings (fig. 1). Small storable-propellant injectors tend to be of the integral-face type; i.e., the face is one continuous piece of material. The concave-face hydrogen-oxygen RL-10 injector and the flat-face hydrogen-oxygen J-2 injector both incorporate a continuous porous face (i.e., one made of a fine-porosity material) for transpiration cooling.

Ring injectors. — Ring injectors allow the use of many small orifices and can produce good propellant distribution. Ring injectors have been used successfully in large thrust chambers with high mass flow and severe injector distribution problems (e.g., the F-1) and with some smaller thrust chambers such as that in the LEM ascent engine. The major problems with ring injectors have been ring leakage, face heating (sec. 2.2.2.2), and orifice inlet control (sec. 2.1.2.1). Ring leakage has produced face erosion on occasion, and some local face damage has been attributed to monopropellants being trapped in face cracks or crevices. The most serious problem, however, has been combustion instability, which was attributed to ring leakage. Performance loss due to ring leakage normally is not significant, primarily because the orifice flow normally is not adversely affected.

Unsatisfactory condition of orifices is one of the more common reasons for injector rejection. With ring-type injectors, in which the rings are drilled before they are inserted into the body, rejection of the rings because of poor orifices results in relatively small cost in time and manpower. In addition, rings can be removed from the bodies of ring-type injectors and a new set inserted without incurring excessive cost and lost time.

Various techniques have been used for attaching rings to bodies. Mechanical methods such as ring rolling, staking, and bolting usually do not provide an adequate seal. Furnace brazing has been used extensively for copper, steel, and nickel rings. Early Atlas and F-1 injectors of 4130 steel were successfully furnace brazed. Differential thermal contraction and subsequent braze joint gaps between copper rings and a 4130 body were corrected by changing the body to 347 CRES, a material with a thermal expansion coefficient very close to that of copper.

Copper rings in copper bodies and stainless steel rings in stainless steel bodies have been successful. The use of oxygen-free high-conductivity (OFHC) copper considerably reduces the brazing problems associated with poor quality copper. Standard nickel plating of copper rings and stainless steel bodies sometimes results in inadequate joint strength; this problem can be corrected by gold plating the copper rings.

Aluminum rings have been dip-brazed into an aluminum body with limited success. Although the injector was quite reliable, severe developmental problems were encountered with the aluminum brazing technique; adequate control of the process is still difficult to maintain.

Electron-beam welding has been used successfully to attach OFHC copper and nickel rings to Inconel-718 bodies and aluminum rings to aluminum bodies (Apollo SPS and Titan Transtage) and to join other materials to each other, particularly when both ring and body are of the same material. Butt-joint electron-beam welding of copper to 347 stainless steel proved to be impractical in some designs because of cracking (ref. 93). Generally, other types of ring welding techniques have proved to be inferior to electron-beam welding because of thermal distortion and cracking problems.

For the Lance booster injector, the aluminum body and rings are integrally cast. This ring casting technique drastically reduced the ring attachment costs. Face casting has not been developed for a production injector for any material other than aluminum.

Some injectors are fabricated by positioning the rings (or part of the rings) on the back side of the injector rather than on the face side. Ring leakage repair in this case can be done without causing orifice warpage, and in addition ring leakage from the back (although still undesirable) is not as critical as leakage into the combustion chamber.

With ring injectors, self-impinging elements can be successfully drilled in the rings before they are installed in the injector body. Opposed impingement elements, however, have not in general been successful when they were predrilled into the rings, because of inadequate orifice alignment. Proper alignment can be obtained by machining the orifices after the rings are in the body (sec. 2.1.2.2).

Integral-face injectors. – Injectors in which the face is an integral part of the body in general do not have joints that can be highly stressed by heat and thus have no face leaks. One of the major problems with integral-face injectors is orifice-inlet control (sec. 2.1.2.1). The problem of orifice rework has adversely influenced the use of integral-face injectors in large sizes. Although repair techniques have been worked out in some cases, they have not always been satisfactory.

Many materials have been successfully used for integral-face injectors; the selection depends primarily on material strength, compatibility, and fabricability.

Porous-face injectors. – Porous-face injectors have been used successfully with engine configurations in which the fuel was injected through the face as a stable gas. In the RL-10 and J-2 engines, the gas is hydrogen; other propellants such as methane, propane, liquid oxygen, and nitrogen tetroxide have been used to a limited degree. In most porous-face designs, the face is attached to the injector body at discrete points (e.g., at the element or between elements) and also around the injector periphery. Although various types of porous materials have been used for injector faces, stainless steel Rigimesh has been the primary material.

Porous faces are transpiration cooled, and the distance between elements does not directly affect the cooling characteristics of the injector face as it does with solid-face injectors. On the other hand, the conduction characteristics of porous injector faces may be poor, and high local heat transfer to the face can result in burnout. Increasing the cooling flow through the face by using a lower density porous material has been successful in preventing burnout.

Porous-face materials frequently display large variations in porosity from spot to spot on a given sheet of material, and the porosity may be further affected by rolling or forming operations. Therefore, local porosity checks are necessary. Porous face contamination and plugging have resulted from combustion products freezing within the injector face, from contaminants within the feed system, from deposits left by the decomposition of face-cooling propellants, and from oxidation when oxygen was a propellant and temperatures were relatively high.

Brazing of porous faces generally is unsatisfactory because braze alloys migrate into the main portion of the face away from the joint surface and plug the face. Welding of 347 CRES Rigimesh is satisfactory, but too large a weld can result in burnout during operation because the local transpiration cooling is eliminated by the welds. EB welding has been used successfully to attach porous faces and minimize plugging. Mechanical metal removal in Rigimesh (e.g., drilling or machining) normally leaves metal smeared along the machined surface; the metal prevents transpiration flow through this surface. When flow through the machined surface is desired, the smeared metal is removed by etching or by the EDM process.

Some performance loss is associated with porous faces as a consequence of mixture-ratio maldistribution, but this loss normally has been reduced to an acceptable value by decreasing the porous-face permeability through use of a higher density material.

Oxidizer-rich operation of the J-2 engine during some cutoff sequences caused overheating and thermal expansion of the Rigimesh injector face, which plastically yielded against the rigid thrust chamber wall. Face cooling then resulted in face shrinkage and misalignment of the outer concentric-tube elements, which produced thrust chamber wall streaking. Reducing the external diameter of the injector face to allow it to expand without yielding eliminated the problem.

2.2.2.2 FACE MATERIALS

Injector face materials suffer from all the limitations of injector body materials (sec. 2.2.1.1). The face, however, often is subject to much higher temperatures than the body, and corrosion is highly accelerated. High face temperature can induce severe thermal strains, with subsequent structural or orifice-flow problems. Corrosion likewise can cause changes in the orifice geometry and thus produce unacceptable flow control, and it can also lead to structural problems.

Aluminum alloys produce very lightweight injectors, and have been successfully used with most storable-propellant combinations. Salt has deposited in the orifices of aluminum injectors when a small nitrogen tetroxide leak occurred over a long period of time; the solution involved system modifications rather than injector redesign. Aluminum injectors have been used successfully with oxygen and with fluorine-containing oxidizers when the face temperatures were low. When the face temperatures were too high, the aluminum was ignited by these oxidizers and the faces burned out.

Copper and some copper alloys are useful for many applications when the heat flux to the injector face is high and the injector cooling system keeps the face temperature relatively low. Also, the high conductivity of these materials effectively dissipates localized hot spots on the injector face and limits damage, if any, to a small area. A variety of chemical compatibility problems has arisen when copper was used with amines, ammonia, hydrazines, nitric acid, or oxides of nitrogen. For example, atmospheric water vapor has combined with residual nitrogen tetroxide to produce nitric acid, which attacked the copper and damaged the orifices in particular. Copper-face orifices have also been badly eroded by chemical attack during hot firing with nitrogen tetroxide when a high injector face temperature was produced.

Stainless steel (e.g., 304, 304L, 321, or 347) is used successfully in many injector faces, in both "solid" and porous form. Stainless steel has a relatively high melting point and ignition temperature, does not normally require a special protective coating, and is readily fabricated. The low thermal conductivity of stainless steel can result in local hot spots in a highly localized heat-transfer environment.

Pure-nickel and nickel-alloy faces have been used with various propellants. The intermediate conductivity of pure nickel and its high melting point make it useful for applications where the face temperature and heat flux are both high.

Rings of 4130 steel, heat treated to improve low-temperature ductility, have been quite satisfactory in LOX/RP-1 service.

2.2.2.3 FACE COATINGS

Refractory coatings have been applied to injector faces on some occasions to eliminate face erosion resulting from excessive heat transfer or inadequate face cooling, and to chemically protect the face material. Ceramic coatings have been applied to protect inadequately cooled regions of the face. Thermal shock induced spalling of these coatings and often led to face erosion and failure. Gradated metal-ceramic coatings with improved thermal shock resistance have been successful in reducing face temperature. Also, refractory metals have been used for face material in regions where standard materials were inadequate; the refractory metal usually fails from oxidation unless the coating is adequately protected.

Fabrication of orifices in injectors that have already been coated is extremely difficult because the coatings are quite hard. Deformed orifice exits frequently have resulted from mechanical drilling through coatings.

Coatings applied to injectors after the orifices have been drilled often result in misdirection of the orifice stream or in reduced orifice flowrate. Insertion of plugs into the orifice or the use of other very local orifice-protection techniques has been unsatisfactory. Anodizing aluminum injectors without adequate orifice protection also has been unsatisfactory. Aluminum injectors can be anodized without affecting orifice geometry by first masking the face around the orifices before initiating the anodizing process.

2.2.2.4 FACE COOLING

Overheating, erosion, and sometimes burnout of the injector face are common problems caused by inadequate face cooling. A large contraction ratio, which results in too much injector face area exposed to the combustion gases, results in overall face overheating. Large thrust chambers operate at low contraction ratios of about 1.25 to 2, and this problem does not occur. Smaller thrust chambers, with contraction ratios of about 3 to 6, normally do not experience this problem when the injection is distributed across the entire face. One experimental injector (Advanced Maneuvering Propulsion Technology program) with a contraction ratio of about 11 overheated badly; the condition was corrected by a complex face-cooling system utilizing high-velocity propellant. A reduction in contraction ratio probably would have eliminated the overheating. However, once an injector or chamber design is fixed, it often becomes impractical to change.

Overall face overheating also is caused by injector elements concentrated only in the central portion instead of being distributed across the entire face. The radial-flow injector in the LEM descent engine and various other pintle and poppet injectors have this type of concentrated injection. Face erosion has been avoided by coatings applied to the face and by regenerative cooling where no propellants were injected. A small localized injection area can also result in radial wind, increase heat transfer to the wall, and sometimes produce oxidizer-rich zones next to the wall.

Local face overheating of injectors is caused by an excessive local heat flux or by an ineffective cooling system. Excessive local heat flux is produced by high-temperature, high-velocity recirculating gas. The recirculating gas-side heat flux can be controlled or minimized by proper element selection and orientation (sec. 2.1.1). When the local heat input to a continuous surface (which can be simulated in one dimension) exceeds the propellant coolant capability, complete wall burnout will occur abruptly. With the two-dimensional heat flow in liquid-propellant injectors, the manifold velocity normally is so low that the burnout heat flux may already be exceeded; however, most of the heat flux into the face of the injectors in absorbed through the walls of the orifices, where the velocity is several times the manifold velocity and the burnout level is very high. When the manifold velocity for the 11:1-contraction-ratio injector was increased to the point at which the propellant could absorb the input heat flux, the resulting manifold dimensions were as small as 0.010 to 0.020 in.; the small size caused severe difficulty in fabrication repeatability.

Increasing the heat flux to the injector face with a standard injector gradually increases the maximum face temperature between orifices (if one assumes, for simplicity, a uniform heat-transfer rate to the injector face) until face erosion starts. Normally, sudden failure as a result of surpassing the cooling burnout limit does not take place. Ignition of the injector face will cause a sudden failure, however. Before the orifice burnout limit is reached, the face region farthest from the orifices normally will have already melted. Local overheating of this type on the Atlas fuel ring was eliminated by placing an additional orifice in the hot-spot region. Decreasing the element size and thus placing the orifices closer together usually reduces local face overheating, even though the overall heat transfer to the face usually increases.

With low-conductivity face material (e.g., 347 CRES), thickening the face of a ring-type injector to improve the two-dimensional heat flow may reduce somewhat the maximum face temperature, the amount of reduction depending on the relative heat-transfer rates through the orifice walls and through the manifold. With high-conductivity materials such as copper, however, thickening the face drastically reduces maximum face temperature. Changing from a low-conductivity material to a high-conductivity material also lowers the maximum face temperature, although the maximum allowable face temperature may be reduced. Changing from a 4130-steel ring to an OFHC-copper ring considerably reduced local ring overheating and erosion in the injectors on the F-1 and Atlas booster. A thicker copper ring (0.250 vs 0.125 in.) was required for strength, although it improved the heat transfer as well.

Figure 30 presents several orifice/face configurations that are related to face thermal problems. The increased high-velocity heat-transfer area of the very high L/d orifice of figure 30(a), in comparison with the standard or low L/d orifice of figure 30(b), is quite effective for reducing face temperature of solid-face injectors and surface temperature of baffles made with medium- or high-conductivity materials. Counter-boring the face side of the orifice, as in figure 30(c), decreases the high-velocity orifice cooling area and results in face overheating.

Poor ring-to-land contact (fig. 30(d)) results in land burning as a result of increased resistance to heat flow from the injector land to the ring. Because of the increased exposure

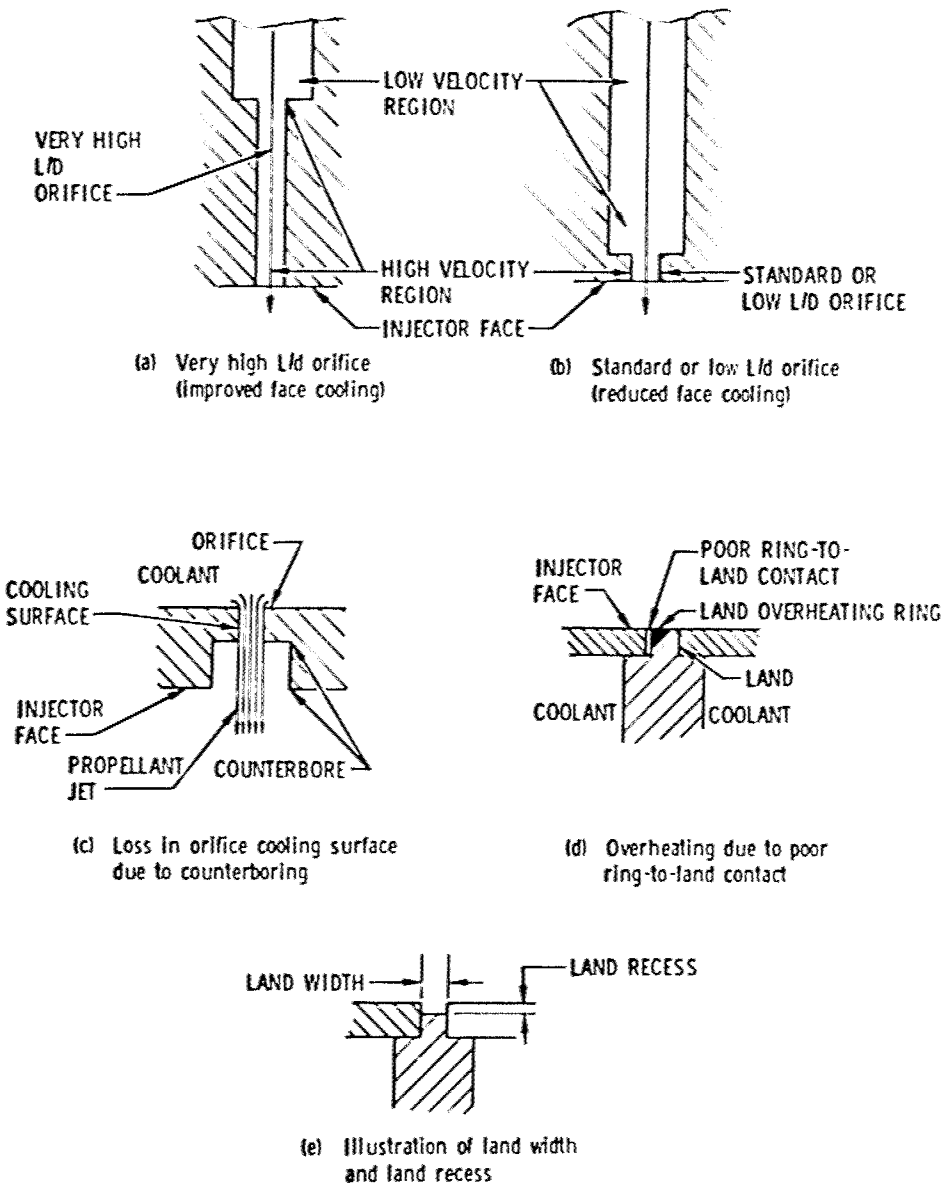


Figure 30. – Injector-face overheating related to orifice/face configuration.

to the hot gases, wide lands are more prone to overheating than are narrow lands. Projecting the copper rings about 0.1 in. above the stainless-steel lands (fig. 30(e)) is necessary in the F-1 injector to protect the lands from erosion. Atlas injectors with similar configurations do not suffer from land erosion even when the lands project above the rings. Face transpiration cooling through a porous face has been successful for injectors utilizing gaseous hydrogen for cooling.

2.2.2.5 INTERPROPELLANT SEALING

Sealing between unlike propellants (prior to injection) is mandatory for all injectors; no leakage is allowed. Severe injector damage from localized explosions frequently has resulted from interpropellant leakage caused by thin webs between propellants, by machining that resulted in small propellant separation distances, by high-porosity metal between propellants, by weld and braze joints between propellants, and by O-ring or gasket seals between propellants. The mixed propellants can be ignited by several means (e.g., flame propagated back from the combustion zone, heat, and shock waves). Designs that contained thin webs between propellants and those that required machining, which can result in little manifold separation distance, often have resulted in walls that failed during operation or in injectors that had to be rejected after completion of fabrication. Maintaining a minimum distance between propellants in excess of 0.100 in. generally eliminated this kind of problem.

Porosity has also resulted in interpropellant leaks when the pores occurred in thin-web sections. Inspection of the injector blank before any machining operations generally has been successful in preventing this type of leakage.

Most of the interpropellant leakage problems have resulted when joints were used between propellants. Single-braze or singe-weld joints (fig. 31(a)) are prone to failure, although they have been successfully used on the Titan program. Double-braze or double-weld joints have been more successful, particularly when vents between the joints (fig. 31(b)) provided a propellant escape path. Problems sometimes have resulted even with double joints and vents when hypergolic propellants leaked simultaneously through both joints. The triple joint with double-vent system (fig. 31(c)) is satisfactory, although cumbersome. Single O-ring or gasket-type seals between propellants cannot be counted on to seal completely. Double seals frequently have leaked and allowed interpropellant mixing; however, double O-ring seals with a vent (fig. 31(d)) have been used successfully on Atlas gas-generator injectors. Development of the double-seal configuration, however, was time-consuming and resulted in many failures before a satisfactory configuration was achieved. A triple seal with double vents would be even more problematic. Effectiveness of the seal depends to a large extent on the propellants used, the seal retainer design, and the type of seal itself.

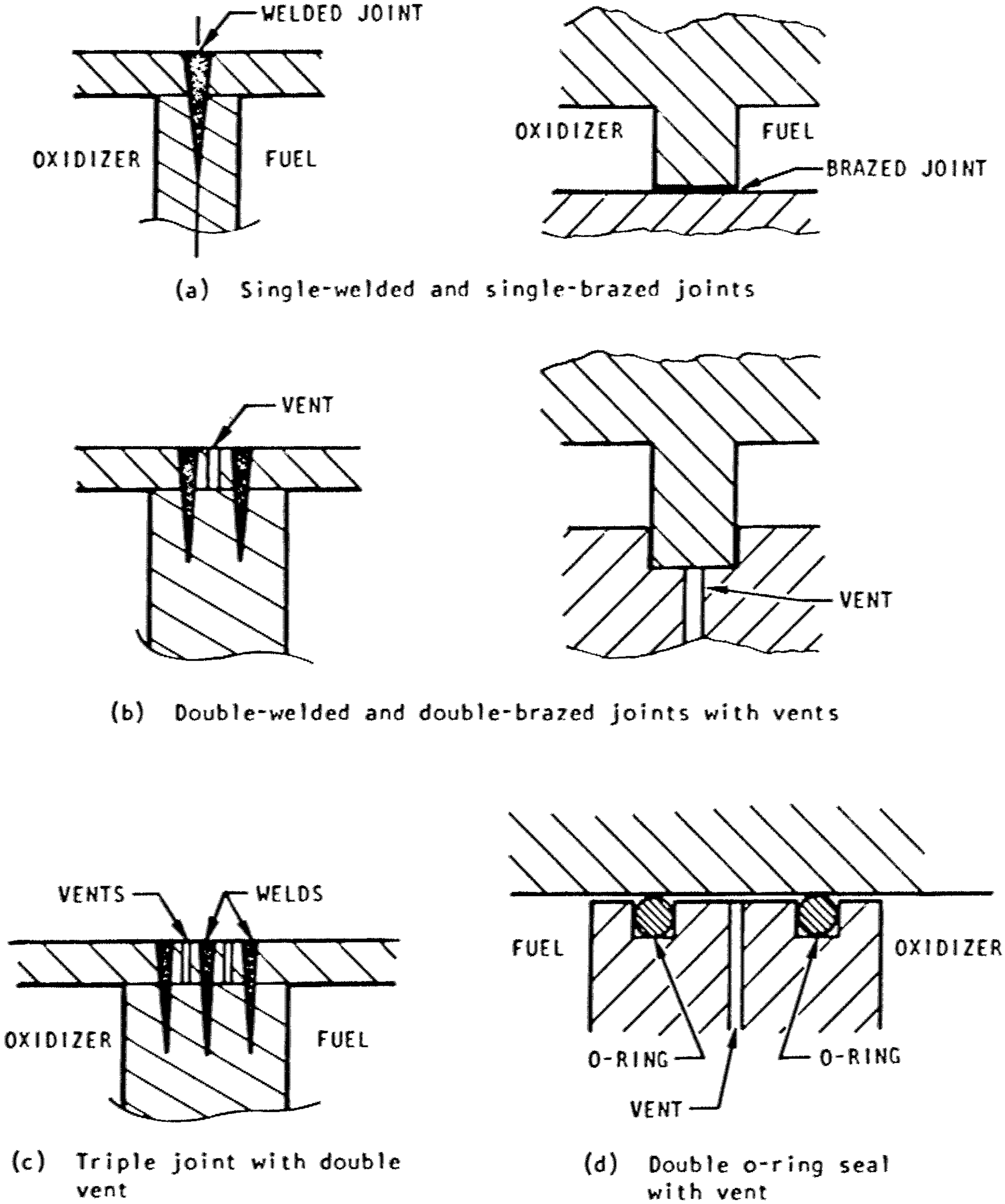


Figure 31. – Construction of interpropellant seals on injectors.

2.2.3 Baffles and Acoustic Absorbers

Baffle and acoustic absorber designs are covered in detail in reference 58. Injector-related problems involving both structural deficiencies and propellant flow maldistribution have resulted primarily when stability problems developed during testing and a baffle or acoustic absorber system had to be added to the injector. Baffle and acoustic absorber systems that were included as part of the original injector design have produced far fewer problems.

2.2.4 Auxiliary Components

Auxiliary components include all of those design elements that are not directly related to the hydraulic-flow characteristics or the structure of the injector. The specific design elements and related problems for auxiliary components vary drastically with the type of injector and the operating conditions. Instrumentation ports, ignition buttons, contamination screens, drain plugs, and seals are the more important auxiliary components.

2.2.4.1 INSTRUMENTATION PORTS

Injector instrumentation ports often are used for data acquisition. These ports and connecting-line malfunctions have resulted both in hardware damage and in lost data.

Bombs for stability evaluation sometimes are mounted into threaded ports on the injector face. Atlas and F-1 injectors contain threaded ports in the fuel rings, and the J-2 bomb mount is on the Rigimesh face. Plugs are screwed into these ports when bombs are not used, and sometimes these plugs leak. The leakage from the Atlas and J-2 injectors was inconsequential; however, occasional plug leakage in the F-1 resulted in combustion "pops" and perhaps self-induced instability. The F-1 leakage was eliminated by tack welding the plugs to the injector face.

Chamber-pressure measurements have been lost when braze flux, braze, or weld plugged the chamber-pressure-pickup line. Also, both brazed-in and welded-in tubes have failed at the injector face connection as a result of joint cracking. Relatively large-volume pressure-pickup lines have failed because the line overheated during startup or during chamber-pressure oscillations. The use of pressure-pickup lines that are drilled through the parent metal instead of tubes increases the heat capacity of the pressure-pickup passage, eliminates failure-prone joints at the face of the injector, and avoids braze- or weld-plugging problems.

Water vapor from the air or from combustion products plugged the chamber-pressure pickup line that passed through the J-2 injector. This problem was solved by bleeding a very small amount of hydrogen gas from the fuel manifold through the pressure-pickup passage.

2.2.4.2 HYPERGOLIC IGNITION BUTTONS

Ignition in thrust chamber assemblies such as the Atlas and F-1 is accomplished with a hypergolic triethylboron/triethylaluminum mixture that is injected through igniter buttons (isolated elements) installed in one of the fuel rings. In the F-1 injector, stainless-steel buttons suffered face erosion when they projected beyond the copper ring. Recessing the face of the button 0.030 in. below the copper ring surface eliminated the erosion.

2.2.4.3 CONTAMINATION SCREENS

Contamination from various sources can plug or restrict orifices. Screens installed in the injector to prevent orifice plugging have themselves become plugged enough to cause excessive pressure drop or flow maldistribution, have failed during starting because of inadequate strength, and have been damaged during removal.

Screen plugging has occurred when the screen surface area was inadequate, the result being an increase in pressure drop or asymmetrical flow downstream of the screen. The use of screens with a large surface area has minimized this problem. Conical screens have been used to increase the screen area within a fixed line diameter.

Contamination screens sometimes are excessively loaded during start, primarily because of the screen location and surge interaction effects. Overdesign of the screens to accommodate these unexpectedly high loads has eliminated this problem without affecting the engine weight significantly.

Screen removal techniques sometimes have damaged the screens or the injector itself. This type of damage was eliminated when removal tools were specifically designed for the particular screens.

2.2.4.4 DRAIN PLUGS

Drain plugs sometimes are used to permit drainage of propellants that remain trapped in the injector between tests. Trapped propellants have caused combustion "pops" at a subsequent ignition. Cleaning solutions that could not be completely removed from the injector have caused similar problems. Injector systems designed to be as self-draining as possible have reduced this problem. In most cases, drain plugs have been positioned at the low points. The actual drain plug design generally is not critical.

2.2.4.5 SEALS

Seals often are used in conjunction with the injector to prevent hot gas or propellant leakage. Hot gases leaking to the atmosphere through the joint between the injector and the thrust chamber can cause both injector and chamber body erosion. In many small injectors, this problem is precluded by attaching the chamber to the injector directly (e.g., by a weld) instead of using a detachable seal. Large injectors are designed so that fuel flows into the combustion chamber if a seal leak occurs, rather than hot gas flowing out. Although this fuel leakage is undesirable, small leaks usually can be tolerated, and even large leaks normally do not result in hardware damage.

Injector O-rings of nearly the same size can be inadvertently transposed during assembly, and the result usually is seal leakage. The use of either identical O-rings or O-rings that were significantly different in size has avoided this problem.

The metal O-ring in the J-2 injector sometimes extruded and caused excessive hydrogen leakage. Changing the design to contain the O-ring in a groove rather than in a step prevented leakage. Soft O-rings frequently have been damaged when the O-ring retainer design was inadequate or when sharp edges contacted and damaged the O-ring during assembly.

3. DESIGN CRITERIA and Recommended Practices

3.1 INJECTOR FLOW-SYSTEM GEOMETRY

3.1.1 Total Element Pattern

The total element pattern shall produce the propellant spray distributions required to satisfy the goals for performance, chamber and injector durability, and stable operation.

The required spray distributions (mixing uniformity and drop size) should be determined with the use of the JANNAF combustion performance models (refs. 1 and 2) before detailed designs are initiated. The inputs to these models are propellant physical, chemical, and transport properties, and chamber configuration. The models are then used to calculate combustion performance as a function of initial mixing uniformity and drop size. The results provide a range of mixing uniformity and dropsize combinations that will result in the required combustion performance and ensure chamber and injector durability and stable operation.

3.1.1.1 ELEMENT SELECTION

The element(s) selected, including both core and peripheral elements, shall meet local limitations essential for durability and shall produce the overall mixing needed for performance.

From the engine specifications, first determine the mixture-ratio and mass limits near the chamber wall. These limits will be different for different wall materials. For example, ablative materials will have mechanical and chemical erosion limits for maintaining structural integrity, whereas most metals will have only a thermal limit. For ablative chambers, the ABLATE program (ref. 94) is recommended; for metal chambers, the boundary-layer-attachment program (ref. 95). For heat-flux calculations, consider that the average mixture ratio in the outer 10 to 15 percent of the mass nearest the chamber wall controls the heat-transfer rates to the wall. Only elements that provide mass and mixture-ratio distributions consistent with the heat-transfer or wall-erosion limits are appropriate near the chamber walls.

Any element that provides highly uniform mixing can be used in the core of the injector.

3.1.1.1.1 Element Types

The element types considered shall be feasible in terms of fabrication, and shall meet the performance and hardware durability requirements of the application.

Before conducting a detailed analysis, make an initial screening of element types and configurations to cut down the extremely large number of possible configuraitons that could be analyzed. Each element type should be considered initially for application in the core of the injector and as peripheral elements near the chamber walls.

Unlike-impinging patterns and hybrid element types generally should not be considered for use near chamber walls. The like-impinging patterns and nonimpinging patterns usually are acceptable in both the core and peripheral regions; however, the preferred orientation may vary with location. Specific decisions, however, should be made only after consideration of the spray characteristics for each element. For many of the unlike-, like-, and non-impinging patterns, data that define mass and mixture-ratio distributions as functions of operating conditions are available; the recommended references for each element designation are listed in tables II and III. When data are not available, conduct cold-flow studies with representative models to define the spray distributions. Final selections of element configurations for further study can then be made.

3.1.1.1.2 Orifice Diameter and Diameter Ratio

The orifice diameter and diameter ratio for the specific element type selected shall provide the maximum possible mixing uniformity and the required spray drop sizes.

Select the appropriate mixing and atomization correlation from the references listed in tables II and III under "Design Correlations" and calculate the orifice diameters and oxidizer/fuel orifice diameter ratios. Note that the correlation used will depend on element type and propellant condition (liquid/liquid or gas/liquid). For elements for which design correlations do not exist, build several elements having a range of orifice diameters and diameter ratios, and conduct cold-flow experiments to define the spray distributions. Finally, select the design that provides maximum uniformity and the desired drop size.

Unlike-impinging elements. – Either the individual element mixing correlations developed in references 6 and 7 or the summary equation in reference 19 should be used to calculate the diameter ratios that produce optimum mixing. If an element type results in a diameter ratio significantly different from that over which the correlations were verified, the element should be eliminated from further study. The resulting oxidizer-to-fuel pressure-drop ratios must also be considered in the final element choice. For common pressurization systems, overall system considerations make it desirable to avoid having the fuel and oxidizer pressure drops widely different. However, in some cases, mixing requirements dictate pressure drops that are different. The size of the element generally should be determined from consideration of dropsize requirements rather than mixing. The orifice size should be determined by using the correlations for the specific element type (tables II and III).

Like-impinging elements. – The relative orifice size generally is not a design parameter for like-doublet elements. The element diameters usually are specified from orifice pressure-drop considerations and drop size. The oxidizer and fuel orifice diameters and, therefore, the diameter ratios (oxidizer to fuel) should be determined by using the dropsize correlations given in reference 4.

Nonimpinging elements. – For the showerhead element, the orifice diameter ratio is not a design parameter. The size of the element should be specified from consideration of drop size. The drop size for the showerhead element should be calculated from the correlation provided in reference 9.

For recommendations on the design of the concentric-tube injector, consult references 5 and 14. The annulus-to-center-jet ratio should be determined from manufacturing limitations, performance, and pressure-drop requirements. Cold-flow characterization of the element is recommended for determining the mixing characteristics and the dropsize distributions for the specific design.

Hybrid elements. – For the pintle injector with individual oxidizer slots located in the pintle, the optimum "diameter ratios" should be determined from reference 10 for liquid/liquid injectors and from reference 38 for gas/liquid injectors. For other pintle designs and for size specification, it is recommended that cold-flow experiments be conducted to determine the spray distributions. Also, review references 96 and 97 for general data on pintle injectors.

For the splash-plate element, consult references 11 and 40 for the recommended design values. Only a limited amount of data is available, and cold-flow experiments are recommended for determining the actual size necessary to provide the required distributions.

3.1.1.1.3 Impingement Angle

The element impingement angle shall provide the required spray distributions without producing unacceptable propellant backsplash.

Unlike-impinging elements. – For the standard unlike-impinging elements, an impingement angle of 60° (included angle) generally is recommended for satisfactory flow characteristics. For the unlike quadlet (Titan), an impingement angle of 100° is recommended. For the standard element types, if impingement angles smaller than 60° are desired, determine the effect of reduction of impingement angle on the spray distributions; propellant backsplash should not be a problem for impingement angles smaller than 60°. Increasing the impingement angle could result in excessive backsplash of propellant. Before selecting an impingement angle greater than 60°, conduct cold-flow experiments in a pressurized vessel at the operating chamber pressure and observe the backsplash characteristics. Use an experimental approach similar to that described in reference 8. Select the maximum impingement angle resulting in acceptable backsplash. In the event that design correlations to specify spray distributions as a function of impingement angle are not available, cold-flow test representative elements and experimentally define these parameters. Reject from further consideration elements that do not produce the desired spray distributions and acceptable backsplash.

Like-impinging elements. – Use a primary impingement angle of 60°, since it has been found to produce acceptable backsplash characteristics. The effect of primary impingement angle on atomization should be determined from the results of reference 4. The cant angle (fig. 2) affects mixing; however, the specific mixing design recommendations depend on where the elements are being employed. When high performance is desired, align the orifices such that the adjacent oxidizer and fuel fans impinge on edge as shown in figure 32(a), and cant the fans toward each other at an included angle of 41° as shown in figure 32(b).

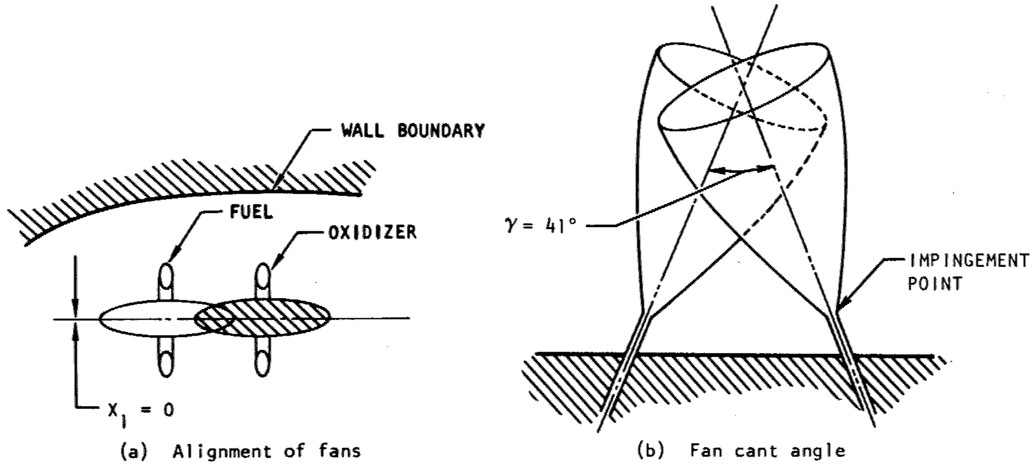


Figure 32. – Recommended design for high performance like-doublet elements.

In the peripheral region near the chamber wall, the oxidizer elements should be inboard of the fuel and the fans should be aligned such that the broad side of the fan is parallel to the wall (i.e., does not impinge) (fig. 32(a)). The distance between the fuel and oxidizer fans depends on the mixture-ratio distribution desired for wall compatibility. Peripheral like-doublet elements generally should not be canted into each other.

Nonimpinging elements. – On the basis of available information, the inner-post chamfer angle for the concentric-tube injector should not be greater than 5°; otherwise, the flow will separate. However, for a new engine, a large number of studies in all probability will be initiated; therefore the latest information should be consulted. Two studies that should be reviewed are references 5 and 14. When no data are available, cold-flow experimentation is recommended for determining the effect of chamfer angle on spray distributions.

Hybrid elements. – The selection of the equivalent impingement angle for the pintle element depends on the pintle design. For slot injection configurations, use 90° impingement angles and, in addition, consult references 10 and 38.

Splash-plate injectors have used splash-plate angles (fig. 8) of about 20°. This parameter appears to have little effect on the spray distributions, so that the final selection of the angle should be decided from design limitations. However, if the resulting angle is greater than about 30°, then use cold-flow studies to verify the resulting flow characteristics.

3.1.1.1.4 Impingement Distance

The design impingement distance shall provide impingement before instabilities within the free jet can cause directional wandering of the jet.

Unlike-impinging elements. – For all of the unlike-impinging element types, the impingement distance should be no greater than 5 to 7 orifice diameters. Since the diameters for the oxidizer and fuel generally are different, an average value should be selected.

Like-impinging elements. – For the like-impinging doublet element, the same specification applies as for the unlike-impinging element: the impingement distance should be no greater than 5 to 7 orifice diameters from the injection point.

Nonimpinging elements. – This parameter is not pertinent to the showerhead element. For the concentric-tube injector, the center-post recess (equivalent to impingement distance) should be no greater than one post diameter. Before final design is determined, consult references 5 and 14.

Hybrid elements. – For the specific pintle element type under consideration, consult the reports listed in tables II and III. For a particular design not included in these reports, initially design an element on the basis of available information and conduct cold-flow experiments to investigate the effect of impingement distance on the spray distributions.

3.1.1.2 ELEMENT ARRANGEMENT

3.1.1.2.1 Element Distribution

The position of one element with respect to another shall provide for maximum interelement mixing and uniform mass distribution consistent with performance and hardware durability requirements.

The elements should be positioned such that equal injector face areas are covered by each element. In most cases, perfectly uniform mass distribution is impossible to achieve because of the large numbers of elements required at the outer diameters and because injector-face heat-transfer requirements limit the maximum allowable spacing between elements. However, an attempt should be made to obtain a mass distribution as uniform as is feasible.

The element distribution characteristics should influence the placement of the elements with respect to each other. The placement should produce increased mixing uniformity from interelement spray mixing. Cold-flow measurement of single-element spray distribution is recommended for determining the element spray characteristics. Profile maps of the distribution then should be used to determine the best interelement positioning such that mixing uniformity will be maximized. Analytically, the overall mixing uniformity of a complete injector can be determined only by a comprehensive analytical model relating injector geometry and flow conditions to local mixture-ratio distribution. One model recommended for use is the Liquid Injector Spray Patterns (LISP) Program described in reference 98. This program currently handles the liquid/liquid unlike-impinging doublet, triplet, and pentad as well as the like-impinging doublet. A Gas/Liquid Injector Spray Patterns (GLISP) Program is described in reference 99. If an analytical model is not available, then cold-flow measurement of the sprays is the recommended experimental method for defining the level of mixing produced by the complete injector. The only drawback to this method is that determination of the overall injector mixing levels cannot be specified before fabrication of a complete injector (or a representative section).

3.1.1.2.2 Element Orientation

The element orientation shall provide near-wall and near-baffle combustion environments that are compatible with the hardware durability requirements.

Unlike-impinging elements generally are not recommended for use near the chamber wall because of the spray characteristics of the element in the outer regions of the spray fan. If unlike-impinging elements are used in the core of the injector, then showerhead fuel elements should be utilized in the periphery of the injector. The jets should be directed at a slight angle ($\approx$ 10°) toward the wall. The exact amount of fuel required should be determined from cold-flow experiments or from an appropriate analytical model such as LISP (ref. 98).

Like-impinging elements are recommended for use near the chamber walls. The elements should be oriented such that the fuel element is closer to the wall than the oxidizer element; in addition, the elements should be oriented so that the fans are parallel to the wall (fig. 32(a)). The specific amount of propellant mass and relative position of the outer fuel to the outer oxidizer doublet should be determined from either cold-flow tests or an analytical model such as LISP.

Nonimpinging elements generally are recommended for use near the chamber wall. The showerhead injector can be used near the wall if the outermost jets carry fuel. The concentric-tube element is excellent for use near the wall since the outer mass generally is fuel.

Hybrid elements generally are not recommended for use near the chamber wall because of the mixture-ratio distributions produced. However, if it is desirable to use this type of element, then the mixture-ratio distribution near the outer portion of the spray should be determined from cold-flow experimentation. Select design parameters that provide acceptable mixture-ratio distributions.

3.1.1.3 COMBUSTION STABILITY CONSIDERATIONS

The injector design shall provide an adequate interface with injector-mounted suppression devices and shall provide sufficient decoupling to preclude feed-system-coupled instabilities.

Adjust the injector design as necessary to assure compatibility of the injector with any required suppression device. When no suppression device is used initially, select an injector configuration that can readily accommodate a suppression device at a later time. Employ injection elements at the downstream edge of a baffle that is regeneratively cooled unless this injection is found to degrade stability.

If stability (acoustic) cannot be obtained with suppression devices, adjust the injector design to promote stability. Employ analytical models (ref. 57) to predict the injector-defined parameters necessary for stability.

The injection pressure drop and orifice length should be made as large as possible within practical limits and as needed to prevent low-frequency instabilities. Use analytical models of the injector and feed system (ref. 60) to select the most efficient methods of achieving stability.

To avoid coincidence of fluid-system natural resonances with a high combustion-process or combustion-chamber response, estimate the oscillatory response characteristics of the injector, feed-system components, and combustion process; adjust design parameters as necessary to avoid feed-system-coupled instabilities. Use analytical models (ref. 57) to aid in estimating these response characteristics.

3.1.2 Individual Orifice Geometry

The individual orifice geometries shall produce the orifice flow characteristics required for the overall propellant flow field.

The results of many cold-flow and hot-firing programs have shown the following trends that should be used as general guides to the influence of orifice geometry on flow characteristics:

- Flow in a sharp-edged orifice normally fills the orifice at its exit (full flow) or else does not contact the orifice at its exit (separated flow). Partial attachment (attachment on one side of the orifice but not the other) can occur as a result of cross velocity at the inlet or inlet burrs with orifices of low L/d. Flow can change under some conditions from full flow to separated flow and back (hydraulic flip).

- Separated flow tends to change to full flow (and the discharge coefficient C_d increases) when the orifice L/d is increased, the orifice pressure drop is decreased, the cross velocity at the inlet is decreased, the inlet is rounded or chamfered, the back pressure into which the stream exits is increased, the vapor pressure of the fluid is decreased, or the amount of dissolved gas is decreased.

- The stream will issue concentric to the orifice centerline for very large values of orifice L/d and for low values of L/d when entry conditions are ideal. For low orifice L/d, the stream will exit at an angle to the orifice centerline when there is a cross velocity or local nonsymmetric turbulence. Increasing orifice L/d, decreasing cross velocity, or contouring or chamfering the orifice inlet will reduce this stream misdirection.

- Cold flow of an orifice or of an entire injector often will result in a C_d other than that produced during hot firing. Orifices that are flowing separated under cold-flow conditions with only sea-level atmospheric back pressure may flow full under hot-firing conditions, particularly during operation at high chamber pressure. In some cases, some of the orifices may flow full and some separated, under either the hot- or cold-flow conditions.

- Under full-flow conditions, the orifice C_d will decrease as the cross velocity increases (ref. 100).

- To avoid hydraulic flip, the orifice L/d should be either short enough to guarantee separation all the time or long enough to guarantee full flow all the time. Intermediate values for L/d (e.g., 4 to 6) are particularly susceptible to hydraulic flip (ref. 101).

- Rounded inlets, chamfered inlets, and converging orifices (orifice inlet larger than orifice exit) produce higher C_d's and lower ΔP's than do sharp-edged orifices. With rounded or chamfered inlets, reproducibility of flow pressure drop becomes more difficult when a small chamfer is used.

3.1.2.1 ORIFICE INLETS

The orifice inlet geometry shall provide reproducible flow characteristics and preclude unstable separated flow, partially attached flow, or stream misdirection.

Rounded, chamfered, or sharp-edged orifice inlets give reproducible flow characteristics. Rounded inlets, which result in the lowest ΔP (highest C_d) and the best flow-stream control, should have an R/d ratio of about 0.3 or more for good reproducibility. An alternate choice is chamfered inlets with a Ch/d ratio of about 2.0 or above. If sharp-edged orifice inlets are used, maintain consistent inlet geometry and avoid burrs by using techniques given below.

Rounded or chamfered inlets should be used to avoid separated or partially attached flow with low-L/d orifices, especially during operation at low chamber pressure.

Irregular orifice inlet conditions (burrs) that cause separated flow, partially attached flow, or stream misdirection should be avoided. Recommended techniques for burr elimination are summarized below.

Accessible inlets. – Contoured inlets should be machined with mechanical cutters or with the EDM or ECM process. The EDM or ECM process can also be used for sharp-edged inlets. Other acceptable methods for sharp-edged orifices are drill – ream – polish, drill – polish – rod – repolish, or drill-into-metal-backup – deburr. Methods suitable for wider ΔP tolerance, as listed below for semiblind and blind inlets, can also be used.

Semiblind inlets (sharp-edged). – The EDM process is recommended for small orifices and EDM or ECM for large orifices or, alternately, mechanical drilling and alkaline etching for aluminum. For wide ΔP tolerances, drilling – deburring by polishing – rodding out inward-protecting burrs – repolishing is a satisfactory method. Alternate wide-tolerance methods are drilling and electropolishing, drilling and vapor honing, drilling into a removable backup material such as salt, and drilling and reaming.

Blind inlets (sharp-edged). – The EDM process should be used for small orifices and EDM or ECM for larger orifices in most materials (metals). Mechanical drilling and the use of an alkaline etch also is satisfactory with aluminum. When injector ΔP tolerances of ± 10 percent or more are permitted, mechanically drill into a removable backup material such as salt or, as an alternate, drill and ream. As a last resort and when ΔP tolerances of ± 15 to 25 percent are permitted, careful standard drilling with no burr control can be used.

3.1.2.2 ORIFICE BORE

The orifice bore length, diameter, and angle of orientation shall produce a stable, reproducible, and properly directed stream.

Flow stability, good reproducibility, and proper stream direction require a full-flowing orifice for best results. The orifice bore geometry, specifically the L/d parameter (or its equivalent for noncircular shapes), generally is used to manipulate the flow characteristics. An orifice L/d of at least 4 should be used to guarantee full flow. Larger L/d's may be required for operation at low chamber pressure ($<$ 100 psi).

The hydraulic-flip phenomenon, with potentially unstable, unpredictable, or improperly directed flow, can be best avoided by controlling the L/d parameter. An equation presented in reference 74 can be used as a first approximation to determine the flow-separation point. Particular attention should be given to the operating chamber pressure (back pressure) range, which has considerable influence on the separation point. To evaluate the effects of propellant cavitation on the hydraulic-flip phenomenon, consult reference 71.

Orifice-inlet cross velocities can affect the orifice-stream reproducibility, direction, and in some cases, hydraulic-flip point or stream stability. The orifice-inlet cross velocities should be uniform and as low as possible, and the orifice should be oriented in relation to the cross flow as shown in figures 14(b), (c), and (e), rather than in opposite directions in relation to the cross flow, as in figures 14(a) and (d). In addition, orifices that are oriented to produce different inlet geometries at the manifold intersections, as in figure 14(f), should be avoided.

Shallow orifice angles between the orifice and the face and orifice surface irregularities that can cause nonreproducibility and misdirection should be avoided. In addition, small orifices ($<$ 0.015 in.) that are prone to plugging, with subsequent nonreproducible and misdirected streams, should be avoided. Select fabrication techniques that will give reproducible results with the prescribed tolerances (sec. 3.1.2.4).

It is recommended that reference 65 be used as the primary design guide for predicting desired orifice flow characteristics; consult references 63 and 64 for additional information. References 5, 80, 81, and 83 provide guidelines for noncircular orifices.

3.1.2.3 ORIFICE OUTLET

The orifice outlet geometry shall maintain the established proper direction of the stream.

Shallow angles between the orifice and the injector face that contribute to stream misdirection should be avoided. Preclude this problem by local spotfacing to increase the effective orifice angle. Drill from the outlet side to prevent undesirable nonsymmetrical breakthrough and outlet burrs that cause stream misdirection. When drilling from the inlet side, use EDM or ECM processes or multiple-pass drilling to prevent exit burrs. Localized flats on the outlet side will improve the outlet geometry on orifices drilled from either the inlet or the outlet sides. Centering devices or other similar schemes should be used to maintain concentricity of concentric-tube injector elements.

3.1.2.4 ORIFICE TOLERANCES

Orifice tolerances shall result in acceptable and consistent flow control.

Tight control on flowrate tolerance should be maintained for injectors with only a few injection elements. A wider tolerance should be allowed for a specified percentage of the total elements for large injectors with many (>100) elements where each orifice is individually measured or calibrated. In these cases, tight control should be considered only for those elements that are near walls or baffles; employ a looser control for the remainder of the elements.

When ΔP (flowrate) tolerances are low, special low-tolerance or selected drills with tolerances of ± 0.0002 in. should be used. For larger orifices with wide ΔP tolerances, the standard drill tolerances such as $+0.0003/-0.0002$ in. may be used.

Gun-drilling techniques are recommended for large close-tolerance orifices that are long and not easily accessible. Drill bushings should be used for all orifices when possible, and all orifices in a given element should be drilled from a single bushing that is stationary during the drilling. Drilling machines with automatic speed and torque control are recommended.

Rotating electrodes are recommended for the EDM process.

3.1.3 Flow-System Geometry Upstream of the Orifices

3.1.3.1 RING GROOVES

The ring grooves shall produce a uniform flow through the orifice inlets.

The ring grooves should be designed to create (1) a propellant flow field that is reproducible from injector to injector, and (2) uniform pressure (or flow) within the rings and between different rings. The characteristics of the individual ring grooves, the feed system upstream of the ring grooves, and the interrelations of these two with each other must be considered when the propellant flow field is being established. In addition, the interaction between the ring-groove characteristics and the orifice characteristics must be considered. The ring-groove flow field should be designed to fit the desired orifice characteristics rather than the reverse.

The inlet velocity to the ring grooves should be maintained as low as possible to minimize the velocity-head pressure (sec. 2.1.3.2). If the velocity head is significant, deflector plates or similar devices to suppress its effect are recommended. An alternate practice is to position the injector orifices at least 1 inlet diameter away from the ring-groove downcomers and thereby avoid the direct impact of the velocity head.

Ring-groove cross velocities should be minimized by using the largest cross-sectional area possible and by tapering the ring groove. Use a distribution ring in the groove when the increased groove area and taper prove to be inadequate. When a distribution ring is used, the number of injector orifices should be kept to a minimum relative to the distribution ring ports, and these ports should not be in line with either the ring-groove feed passages (downcomers) or injector orifices.

Standard techniques for calculating fluid flow can be used to calculate the pressure and velocity distributions. However, because of the potential ring-groove design complexities, cold-flow experiments are recommended as a check on the pressure and flow distribution and as a tool to aid in optimizing the design.

3.1.3.2 DOWNCOMERS

The downcomer flow passages shall supply uniform and reproducible flow to the ring grooves or orifices and shall minimize pressure losses.

The downcomer flow passages should be designed for minimum propellant velocities, primarily to minimize velocity head and thereby enchance the possibility of uniform flow to the orifices; in addition, low velocities will minimize injector ΔP. A well-rounded (contoured) entrance is best for minimum ΔP, followed by a wide-chamfered entrance, and then a square-edged entrance. When a higher pressure drop through the downcomer is required, reduce the downcomer diameter only at the downcomer inlet section.

The downcomer flow should be reproducible from injector to injector and from passage to (like) passage in a given injector. Good downcomer entrance reproducibility will support this goal, since the entrance consistency strongly affects the C_d and ΔP consistency. When using sharp-edged entrances, eliminate entrance burrs.

In order to provide minimum velocity, a design like the flat-spray configuration of figure 19(d), which results in maximum full-flow exit area, should be selected in conjunction with downcomers from accessible manifolds such as domes. For lower flowrates, the tapered design of figure 19(c) may be adequate but should be used only up to a total taper angle of 15°. The straight circular design of figure 19(b) should be used only for low downcomer flowrates.

For downcomers from inaccessible manifolds such as radial or transverse manifolds, use a design such as the tapered and drilled configuration of figure 20(c), which results in maximum full-flow area and restricts the flow in the central portion of the downcoming stream. For lower flowrates, the narrow tapered slot design of figure 20(b) with an $L/d \geqslant 4$ may be used. The straight circular design of figure 20(a) is recommended only for very low flowrates. Downcomers that are as wide as, or wider than, the ring groove are preferred over ones that are narrower.

Do not allow a mismatch between downcomer and injector orifice centerlines when the orifice and the downcomer are directly in line and downcomer-to-orifice diameter ratios are small ($\leqslant 5$). When possible, all downcomer-to-orifice orientations should be similar.

3.1.3.3 DOME MANIFOLDS

The dome manifold geometry shall result in uniform flow through the outlet passages.

Keep propellant inlet velocities to the dome and velocities in the dome low ($\leqslant$ 10 ft/sec). Low velocities will reduce the potential variations in static pressure and flow at the outlet passages and also tend to minimize nonreproducible flow characteristics.

A deflector plate (fig. 21(a)) or a distribution plate (fig. 21(b)) should be used beneath single or multiple inlets producing high, axially directed propellant inlet velocities. Multiple inlets are recommended where feasible. When nonsymmetrical inlets are used at the back of the dome, a distribution plate should be employed, as in figure 21(c).

A distribution ring (fig. 21(d)) or possibly a distribution ring with tangential manifolding is recommended for domes with side inlets. In some designs, localized deflector plates may be used opposite the inlets. Again, multiple inlets should be used where feasible.

Inlets for high-velocity flow should be located away from the vicinity of the dome outlets (fig. 22(b)) and should not aim flow directly across the outlets (fig. 22(a)).

3.1.3.4 RING MANIFOLDS

Ring manifold geometry shall produce uniform flow through the manifold outlet ports.

Design manifold inlet lines for a propellant exit velocity as low as possible; in addition, maintain low velocities within the manifold.

Use multiple inlets wherever feasible. Feed regenerative-coolant-passage flow directly into the ring manifold rather than collecting the flow from the passages into a fewer number of lines before injecting it into the ring manifold. To prevent direct impingement of the inlet flow on outlet ports, use tangential inlets when possible.

When manifold outlet ports are subject to direct impingement of inlet flow, use a deflector plate (fig. 23(a)) or offset the inlet port relative to the outlet port (figs. 23(b) and (c)). Tapered ring manifolds or distribution rings are recommended for uniform pressure and flow distribution around the manifold. For long flow paths around the ring manifold, include both friction and contour losses in pressure-drop calculations.

Distribution rings with variable port sizes should have the maximum feasible number of distribution ports per manifold outlet port. Do not put a distribution-ring port directly in line with the manifold inlet flow or a manifold outlet port.

3.1.3.5 RADIAL AND TRANSVERSE PASSAGES

The static pressure and velocity distribution in radial and transverse passages shall produce uniform flow through the passage outlet ports.

Maintain low velocities and low static pressures in radial and transverse manifolds whenever possible. Tapered manifolding (fig. 24(c)) is recommended for maintaining a uniform manifold velocity. A step at the end of the tapered manifold to compensate for flow stagnation should be considered. As an alternate, use stepped manifolding as shown in figure 25. Low uniform velocities and static pressures are also recommended for radial manifolds as used with concentric-tube injectors.

Contoured inlets are recommended for more consistent and predictable flow in the passages. An alternate choice is to use a chamfered inlet with a relatively large chamfer-to-radial-port diameter ratio (sec. 2.1.2.1).

Avoid locating manifold outlets in the contoured portion of a contoured inlet, immediately downstream of a sharp-edged or chamfered inlet, or immediately downstream of a step. If one outlet per step is used with stepped radials, locate the outlet just upstream of the following step. If the manifold is stepped, or if outlets that flow a large proportion of the manifold flow are placed near each other, experimentally verify the analytically calculated flowrates through the manifold outlets. Cold-flow experiments for all facets of the radial and transverse manifold designs are recommended for checking the flow distribution and aiding optimization.

3.1.3.6 GENERAL FLOW SYSTEM UPSTREAM OF THE ORIFICES

Auxiliary components in the injector flow system or the flow system in general shall not result in unacceptable orifice flow distribution.

In the initial injector design, make allowances for the insertion of nonfeed-system-related components such as instrumentation and igniter passages that eventually may be required. If possible, these components should be designed as an integral part of the injector; otherwise they should be designed to prevent flow-system maldistribution.

Avoid flow splitters by using a low velocity in the inlet line or by using inlets that are symmetrical to the two downstream flow passages (fig. 26(a)). Do not use inlets that are nonsymmetrical to the two downstream flow passages (fig. 26(b)). When flow splitters are used, determine their flow and hysteresis characteristics across the entire range of inlet flow conditions, not just at the nominal point.

Uniformity of flow distribution may be enchanced by minimizing the number of turns that the propellant makes through the injector and by keeping the total pressure drop within the injector upstream of the orifices to less than approximately 25 percent of the orifice pressure drop, thereby minimizing the feed-system variation effects. If additional pressure drop is needed, use a single restrictor through which all of the propellant flows, in preference to several restrictors in parallel.

Avoid trapping bubbles in stagnation regions at the top, relative to gravity, of a manifold, as in figure 27(a). Taper the manifold to increase the velocity in the bubble-trap area. Avoid trapping bubbles at the end of a radial by a large stagnation region beyond the end of the last outlet from the radial and the radial attitude, as in figure 27(b). Reduce the radial length or place the last outlet closer to the end of the radial.

3.2 INJECTOR ASSEMBLY

The injector-assembly design shall complement the flow-system-geometry design.

The injector-assembly design efforts should be accomplished in parallel with the flow-system-geometry design. Shift back and forth as necessary between the two design phases to obtain an acceptable balance.

3.2.1 General Structure

3.2.1.1 BODY MATERIALS

3.2.1.1.1 Corrosion Resistance

Injector body materials shall be resistant to or protected from corrosion under all operating conditions.

Corrosion-resistant stainless steels such as 347 CRES and certain aluminum alloys are recommended for use with all common propellant combinations. Copper and copper alloys and nickel and nickel alloys can be used for most propellants with the notable exception of nitric acid. Consult references 88 and 89 for specific information on propellant/metal compatibility.

Do not use materials that are easily corroded by the atmosphere (e.g., most high-strength steels). If materials of this nature are used, use a plating that will afford corrosion protection, but only if the plating process is carefully controlled. Electroless nickel plating is suggested, if compatible, since it can be readily deposited on inaccessible surfaces.

3.2.1.1.2 Ductility

Injector body materials shall retain acceptable ductility at the propellant supply temperatures.

Materials with good low-temperature ductility such as 347 CRES, copper, aluminum, nickel, and proven nickel alloys should be used for cryogenic propellant service. Heat-treated 4130 steel may be used for liquid-oxygen service. The ductility of most common metals and alloys is acceptable for operation at temperatures from about 70° to 500°F.

3.2.1.1.3 Flaws

The injector body material shall be free of unacceptable flaws.

In general, vacuum-melt materials and aircraft-quality materials rather than standard materials should be used. In particular, use vacuum-melt materials for injectors with welded joints. Inspect forged blanks ultrasonically to detect local porosity.

3.2.1.2 WELD JOINTS

Welding shall not produce structural distortion in the injector body or element misalignment.

Heavy welds should be made early in the fabrication sequence, with finish machining accomplished after the welding. Do not weld near the injector orifices if unacceptable distortion is possible. If welding near the orifices is required, drill after welding or consider EB welding.

Avoid welding electroformed nickel bodies or other materials with high residual internal stresses.

3.2.1.3 BRAZE JOINTS

Injector assembly braze joints shall not leak.

Avoid locating braze joints in areas of high thermal stress. Also avoid (1) porous braze materials, (2) materials that are prone to shrinkage, and (3) braze-runoff triggers such as slots and wicks such as burrs. Hand brazing or other brazing techniques that result in uneven heating or cooling and braze joint stresses should be avoided.

Design the braze joint to provide the proper clearance relative to the alloy used and provide for a 100-percent inspection of the joint after brazing.

3.2.1.4 CLOSEOUT PLUGS

The injector shall be free of leakage through closeout plugs.

Injector bodies should be designed to preclude the use of closeout plugs, particularly small plugs and plugs between unlike-propellant manifolds. However, if plugs are required, they should be located where they can be inspected and repaired readily.

Welding or brazing is recommended for installing closeout plugs into the injector body. The particular method selected will depend on the materials used, the accessibility, and the geometry of the design itself.

3.2.1.5 POSTS

Center posts of concentric-tube injector elements shall remain concentric within acceptable limits and shall resist cracking.

Centering devices should be used to maintain concentricity throughout fabrication processing and test operations. In many designs, however, the centering devices are not adequate because of a tolerance buildup that may be impractical to correct. Thus, other centering techniques are recommended; viz., machining and processing to minimize eccentricity and mechanical straightening.

Welding or brazing processes that result in a mismatch between the injector face or outer tube diameter and the center post should be minimized. If the welding or brazing does produce mismatch, match drill as necessary to produce acceptable concentricity, particularly in those elements near the chamber wall or baffles.

When mechanical straightening is required, use a ductile post material such as 347 CRES and use long posts. If a less ductile material such as Inconel 718 is used, decrease the stress concentrations in the center posts developed by bending; for example, use a large fillet radius at the base as shown in the design in figure 28. Also, anneal posts that are made of brittle material.

3.2.1.6 FACE AND BODY RIGIDITY

The injector face and body rigidity shall be adequate to prevent an unacceptable resonance with the combustion process.

The natural frequency of the injector design should be established to fall outside the potential frequency ranges of the combustion process. The injector frequency can be adjusted through the use of stiffening ribs (an inner row of tie rods or posts between dome-type manifold and the injector (large injector)), by using a contoured (concave) injector face, or by the less desirable method of changing the overall thickness.

3.2.1.7 STRUCTURAL SUPPORTS AND FLOW DEVICES

Structural supports and flow devices shall not detach or loosen.

Supports and flow devices should be made integral with the injector whenever possible. Parts that are not integral should be designed to avoid stress concentrations in the weld or braze joints used for attachment. Shapes sensitive to failure from vibration or flutter as well as designs that are prone to failure from surges should be avoided.

3.2.1.8 CONTAMINATION CONTROL

The injector shall be free of areas that tend to trap contaminants

Avoid cracks and crevices of the type shown in figure 29(a). Design instead to open up the crack as shown in figure 29(b). Drain plugs are recommended in areas where normal draining, flushing, or purging techniques are ineffective.

3.2.1.9 REMOVAL AND HANDLING PROVISIONS

Removal and handling provisions shall preclude injector damage.

Threaded holes and jacking screw equipment or other effective devices should be provided to help separate injectors or injector components from their mating components when there is a potential binding problem.

Baffled injectors should contain three or more standoff buttons on the baffles positioned to minimize handling damage. For very large baffled injectors such as that on the F-1, specify procedures that require a face-up position during handling. For flat-faced injectors without baffles, use at least three standoff buttons, recess the face, or use a concave face. Injectors do not need additional orifice protection if the ring lands project beyond the rings or the flow control orifices are located upstream of the face.

Use only shipping containers that are designed as a part of the overall injector design, not just any container that happens to be available. Design the shipping container so that the injector will fit in only one position. Do not use shipping-container inner surfaces that are relatively hard in comparison with critical injector surfaces that they contact. Do not use loose or soft packing material that can become lodged in orifices.

Develop and utilize injector cleaning and packaging procedures that will prevent contaminants from plugging flow passages or reacting with the propellants.

3.2.2 Injector Face

3.2.2.1 FACE TYPES

3.2.2.1.1 Ring Injectors

Ring injectors shall be leak free and shall simplify injection orifice control.

The ring concept should be considered for all injectors, particularly for large injectors that require a complex manifold system to feed propellants to many orifices. Also, consider the ring concept for injectors with many orifices that are a part of the injector face and are difficult to repair in place.

Self-impinging elements should be drilled before ring insertion. For opposed impinging elements, EDM the orifices or mechanically drill and then etch the orifices after ring insertion (sec. 2.1.2).

Furnace brazing or electron-beam welding is recommended for installing copper, steel, or nickel rings into bodies of the same material. Electron-beam welding should be used for aluminum rings and bodies; do not braze. Consider casting aluminum rings integral with the body. Do not electron-beam weld copper rings to stainless steel bodies. If possible, position the rings on the back side of the injector rather than on the face. Do not use mechanical attachment methods such as ring rolling, staking, or bolting to seal the propellants.

When furnace brazing, use ring and body materials with identical thermal expansion coefficients (identical materials) or with very similar coefficients (e.g., copper and 347 CRES). Do not use ring and body materials with significantly different thermal expansion coefficients (e.g., copper and 4130 steel). Nickel plating on both ring and body joint areas is recommended for furnace brazing assemblies of 4130 or brazing copper rings and stainless steel bodies. If stronger joints are needed, gold plate the copper rings.

3.2.2.1.2 Integral-Face Injectors

Integral-face injectors shall simplify fabrication while allowing adequate orifice inlet control.

Integral-face injectors are recommended for avoiding potential leakage and for simplifying fabrication of small injectors. Large integral-face injectors should be avoided unless there is a satisfactory orifice repair technique. Since injector face materials are the same as the body materials, the material selected must be compatible with the body structural requirements as well as with the face thermal and structural demands.

3.2.2.1.3 Porous-Face Injectors

Porous-face injectors shall permit adequate face cooling, minimize performance loss, and avoid unacceptable restrictions from foreign material.

A porous injector face (and the corresponding transpiration cooling) is recommended when conductive/convective cooling techniques through a continuous or ring-type face are inadequate or unduly complex. Use a face-coolant propellant such as hydrogen or methane (generally in the gaseous state) that does not leave a solid deposit on or within the face material. Do not depend on conduction through the face to contribute significantly to face cooling. If a face-overheating potential develops, decrease the density of the porous face material (to increase the flow) or use a solid face of high-conductivity metal. Avoid using large welds on the face and do not braze.

If porosity through a machined surface is required, use a technique such as the EDM process that does not smear surface material. If the surface is smeared and made impermeable by mechanical machining or drilling, use an etch to remove the smeared material. If a machined surface is to be impermeable, use mechanical machining techniques that smear the surface. Check the consistency of the raw material by making localized porosity checks.

Allow space for face thermal expansion and contraction, so that plastic yielding of the face material does not occur.

3.2.2.2 FACE MATERIALS

Injector face materials shall exhibit acceptable propellant compatibility characteristics and capability for being cooled

Stainless steel should be used for all propellant combinations and injector configurations in which the heat flux to the injector is not more than 2 Btu/(in.^{2}-sec) and the weight is within specifications. Stainless steel face temperatures $\leq$ 1600°F are acceptable.

When heat flux to the face is 10 Btu/(in.^{2}-sec) or more, use copper, particularly with fluorine, interhalogens, and oxygen propellants. With copper, face temperatures $\leq$ 1000°F are acceptable. Do not use copper with nitric acid, or with nitrogen tetroxide unless nitric acid formation between tests can be prevented and metal temperature in contact with the N_2O_4 can be kept below 500°F.

Nickel can be used for heat flux of 2 to 10 Btu/(in.^{2}-sec) and face temperatures up to 1300°F with most propellants. Do not use nickel with nitric acid. High-strength nickel alloys are recommended to minimize weight, particularly when face temperatures are relatively high ($\approx$ 1300°F).

Aluminum alloys can be used for conventional storable-propellant combinations, heat fluxes of 2 to 8 Btu/(in.^{2}-sec), intermediate to low face temperatures ($\leq$ 400°F), and light weight. They should not be used with fluorine-containing oxidizers or oxygen unless face temperatures can be kept below 400°F. Avoid exposure to nitric acid formed from nitrogen tetroxide between tests.

Most high-strength steels corrode under atmospheric conditions and should not be used. Also, most of these materials, such as 4130 steel, cannot be used when heat flux exceeds ≈ 2 Btu/(in.^{2}-sec).

3.2.2.3 FACE COATINGS

Injector face coatings shall prevent face damage from chemical attack or excessive heat.

Injector face coatings should be used only if adequate face cooling cannot reasonably be obtained by propellant cooling, either through the orifices or by regenerative passages behind the face where there are no orifices.

When a face coating is used, mask the face around each individual orifice before applying the coatings. Do not mechanically drill through coatings. Use metal-ceramic gradated coatings rather than pure ceramic coatings, and use oxidation-resistant materials to protect refractory metal coatings.

3.2.2.4 FACE COOLING

Injector face cooling shall be adequate to prevent erosion or other failure due to overheating.

A chamber with a small contraction ratio (under 6 and preferably under 3) should be selected when practical to minimize injector face area and prevent overall injector-face overheating. Also, consider increasing the cooling capability of the propellant by using high-velocity flow in the manifolds behind the face, and distribute the injection orifices across the entire injector face rather than concentrating them in a given area such as the center. Injector types that concentrate the injection in the center should be used only when there is considerable prior experience with that type of pattern. If face heating occurs, consider refractory coating the face and using regenerative cooling in the regions where there is no propellant injection, or consider porous-face cooling.

Small orifices distributed uniformly across the injector face will aid in preventing local as well as overall face overheating. If local face overheating occurs, place an additional orifice in the hot spot.

Two- or three-dimensional heat-transfer calculations should be used to determine optimum ring thickness. Use thick rings for a drastic reduction in the maximum temperature of high-conductivity metals, a significant reduction in intermediate-conductivity metals, and a small reduction in low-conductivity metals. The highest conductivity metal suitable for the application should be used for the injector face. Consider the melting point of the metal in determining the suitability.

Orifices with high L/d values (fig. 30(a)) rather than low L/d orifices (fig. 30(b)) are recommended for improved heat transfer. Do not counterbore the face side of the orifice as in figure 30(c).

For ring-type injectors, narrow lands rather than wide lands (fig. 30 (c)) are recommended. Avoid the ring-to-land gap as shown in figure 30(d) and project high-conductivity rings beyond low-conductivity lands as shown in figure 30(e).

Consider the use of transpiration cooling for the injector face when gaseous hydrogen or a similar propellant is used.

3.2.2.5 INTERPROPELLANT SEALING

Interpropellant sealing shall be adequate to prevent interpropellant mixing.

Use parent metal between propellants whenever possible and maintain a minimum of 0.100 in. of parent metal between propellants in the finished injector. Inspect the injector blank for porosity prior to machining. Avoid designing a break in the injector material between propellants and then attempting to seal the break by brazing, welding, or using a mechanical sealing system.

If interpropellant seals are required, use a triple seal with double vents like that shown in figure 31(c). For nonhypergolic propellants, consider substituting the simpler double seal with single vent shown in figure 31(b). O-ring or gasket systems are not recommended, although the double or triple seals with vents can be used with cryogenic propellants if propellant overboard leakage is allowed (fig. 31(d)). Never use a single O-ring seal, or a double O-ring seal without a vent between the O-rings.

3.2.3 Baffles and Acoustic Absorbers

The design and installation of baffles and acoustic absorbers shall not result in problems with injector flow or structure.

Baffle or acoustic-absorber systems should be designed as part of the original injector design effort. If there is a reasonable probability that baffles or acoustic absorbers may be added at a future time, design the injector initially so as to minimize structural and hydraulic problems when they are added.

3.2.4 Auxiliary Components

3.2.4.1 INSTRUMENTATION PORTS

Instrumentation ports and lines shall not cause hardware damage or result in lost data.

Bomb-boss ports or similar bosses in the injector face with a leakage potential can cause combustion pops or combustion instability. These leaky ports should be positively sealed, possibly with plugs that are tack welded in place.

If possible, the chamber-pressure-pickup line through the injector should be machined in the parent metal. If this is not possible and an auxiliary line is used, weld the line to the injector face in preference to hand brazing.

When hydrogen is used as a propellant, consider bleeding a small amount of the hydrogen gas from the manifolding and passing it through the chamber-pressure-pickup line, thus preventing possible ice formation.

3.2.4.2 HYPERGOLIC IGNITION BUTTONS

Hypergolic igniter buttons shall not erode.

Igniter buttons should be recessed behind the injector face to preclude erosion.

3.2.4.3 CONTAMINATION SCREENS

Contamination screens shall provide a constant pressure drop and symmetrical flow and be resistant to damage.

The screen surface area should be sufficiently large that foreign particles trapped in the screen will not cause a significant increase in pressure drop or a nonsymmetrical downstream flow distribution. Screen surface areas within a fixed line size may be increased by adopting conical rather than flat-surface designs.

Screen overdesign is recommended for accommodating potentially high surge loads during start and thereby minimizing damage. Also, screen removal tools should be specifically designed to prevent handling damage to the screen. Screen concepts should be included as part of the original injector design. If screens are not specified at the start of the program, make provisions for trouble-free incorporation of the screen later in the program.

3.2.4.4 DRAIN PLUGS

The injector design shall provide means for eliminating residual propellants or cleaning fluids that cause combustion irregularities at ignition.

The injector should be designed to be as self-draining as possible; install drain plugs if necessary at the low points where a potential trap exists.

3.2.4.5 SEALS

Seal leakage shall not result in injector or other hardware damage

Whenever possible, attach injectors to the chambers and manifolds to the injectors directly (e.g., by a weld) rather than with a detachable seal. This kind of attachment is particularly applicable to small injectors, but should be considered also for large injectors. If possible, injectors that are attached to the chamber with a detachable seal should be designed so that if the joint leaks, fuel flows into the chamber rather than hot gas out. However, the injector should be designed not to leak.

When two or more O-rings are used in an assembly, use either identical O-ring sizes or two sizes that are significantly different and cannot be inadvertently interchanged. Position O-ring-type seals into a groove rather than a step in order to avoid detrimental extrusion. Avoid sharp edges that can damage O-rings on contact during assembly.

APPENDIX A

Conversion of U.S. Customary Units to SI Units

Physical quantity	U.S. customary unit	SI unit	Conversion factor[a]
Angle	degree	radian	1.745×10^{-2}
Density	lbm/in.^{3}	kg/m^3	2.768×10^{4}
	lbm/ft^3	kg/m^3	1.602×10^{1}
Force	lbf	N	4.448
Heat flux	Btu/(in.^{2}-sec)	W/m^2	1.633×10^{6}
Length	ft	m	3.048×10^{-1}
	in.	cm	2.54
	micron	μm	1.00
Mass	lbm	kg	4.536×10^{-1}
Pressure	atmosphere	N/cm^2	1.013×10^{1}
	psi (lbf/in.^{2})	N/cm^2	6.895×10^{-1}
Surface tension	dynes/cm	N/cm	1.00×10^{-5}
Thrust	lbf	N	4.448
Velocity	ft/sec	m/sec	3.048×10^{-1}
Viscosity, dynamic	lbm/(ft-sec)	N-sec/m^2	1.488

[a] Multiply value given in U.S. customary unit by conversion factor to obtain equivalent value in SI units. For a complete listing of conversion factors for basic physical quantities, see Mechtly, E. A.: The International System of Units. Physical Constants and Conversion Factors. Second Revision, NASA SP-7012, 1973.

APPENDIX B

GLOSSARY

Term or Symbol	Definition
A	width of fuel injection annulus in pintle injector (fig. 4)
B_{in}	length of a uniform inward burr (fig. 17)
B_{re}	length of a uniform reentrant burr (fig. 17)
C	cross-influence term, eq. (5) (defined in ref. 10)
Ch	chamfer diameter
C_d	discharge coefficient, dimensionless
Ch/d	chamfer diameter/bore diameter
c^*	characteristic exhaust velocity
cavitation	formation of vapor bubbles in a flowing liquid whenever the static pressure becomes less than the fluid vapor pressure
cryogenic	fluids or conditions at low temperatures, usually at or below –238°F (222°R)
$\bar{D}$	mass median drop size
DER	distributed energy release
d	diameter
dome manifold	a manifold that spans the back of the injector
downcomer	axial feed passages from the rear of the injector
EB	electron beam
ECM	electrochemical machining
EDM	electrical discharge machining
electroforming	production of seamless hollow containers by electrodeposition

Term or Symbol	Definition
electroless plating	chemical reduction process for deposition of a metallic coating
free stream	length of the jet from the orifice exit to the point of impingement with another jet or a surface
GLISP	gas/liquid injector spray pattern
hypergolic propellants	propellants that ignite spontaneously on contact
K_{prop}	correction factor for propellant physical properties
L	length
LEM	lunar excursion module
LISP	liquid injector spray pattern
ℓ	length of oxidizer slot in pintle injector (fig. 4)
M	empirical mixing factor (table IV, eq. (1))
MR	mixture ratio: (mass flowrate of oxidizer)/(mass flowrate of fuel)
P	pressure
P_{ch}	chamber pressure
P_D	dynamic pressure ratio, $\rho_f V_f^2 / \rho_o V_o^2$
$\frac{P_c}{P_j}$	velocity profile parameter: dynamic pressure at center of jet/mean dynamic pressure of jet
R	orifice inlet radius
R/d	inlet radius/bore diameter
RCE	reaction control engine
RCS	reaction control system
radial passage	manifold passage that is normal to the injector flow direction
regenerative cooling	cooling of part of an engine by propellant being delivered to the combustion chamber

Term or Symbol	Definition
Reynolds number	a nondimensional parameter (Re) representing the ratio of the momentum forces to the viscous forces in fluid flow
S	width of oxidizer slot in pintle injector (fig. 4)
SL	sea level
SPS	service propulsion system
storable propellant	a propellant with a vapor pressure such that the propellant can be stored in a specified environment (earth or space) at moderate ullage pressures without significant loss over the mission duration
TCA	thrust chamber assembly
V	injection velocity
Vac	vacuum
$\dot{w}$	mass flowrate
winds	flow of gases from regions of high pressure to regions of low pressure as a result of mass and mixture-ratio maldistribution. When the flow is radial to equilibrate pressure across a given axial location, the movement is termed "radial wind"
X_1	fan spacing (defined in fig. 2)
γ	inclination or cant angle of impinging jets
Δ	incremental change in a variable
θ	jet impingement angle
μ	dynamic viscosity
ρ	liquid density
σ	surface tension

Subscripts

c	center or central
ch	chamber

Subscripts

f	fuel
fs	free stream
g	gas
j	jet
L	liquid
MME	maximum mixing efficiency
o	oxidizer
or	orifice
ou	outer
p	passage
θ	jet impingement angle

Materials[1]	Identification
A-50	50/50 blend of N_2H_4 and UDMH, propellant grade per MIL-P-27402
CRES	corrosion-resistant steel
fluorine	elemental fluorine (F_2) in its liquid form (LF_2) used as a cryogenic propellant per MIL-P-27405
Inconel 718, X-750	trade names of International Nickel Co. for austenitic nickel-base alloys
IRFNA	inhibited red fuming nitric acid, propellant grade per MIL-P-7254
LOX	liquid oxygen, propellant grade per MIL-P-25508
N_2H_4	hydrazine, propellant grade per MIL-P-26536
N_2O_4	nitrogen tetroxide, propellant grade per MIL-P-26539 or MSC-PPD-2

[1]Additional information on metallic materials herein can be found in the 1972 SAE Handbook, SAE, Two Pennsylvania Plaza, New York, N.Y.; in MIL-HDBK-5B, Metallic Materials and Elements for Aerospace Vehicle Structures, Dept. of Defense, Washington, D.C., Sept. 1971; and in Metals Handbook (8th ed.), Vol. 1: Properties and Selection of Metals, Am. Society for Metals (Metals Park, Ohio), 1961.

Materials	Identification
nickel 200	designation of International Nickel Co. for commercially pure nickel
OFHC copper	oxygen-free high-conductivity copper
Rigimesh	trade name of Aircraft Porous Media, Inc. (Glen Cove, NY) for porous plate formed by compressed, sintered stacks of wire screen
RP-1	kerosene-base high-energy hydrocarbon fuel, propellant grade per MIL-P-25576
Shellwax 270	trade name of Shell Chemical Co. for a paraffin wax used to simulate propellant in dropsize studies
Tens-50	trade name of Rockwell International for high-strength cast aluminum alloy
UDMH	unsymmetrical dimethylhydrazine, propellant grade per MIL-P-25604
304, 304L, 321, 347	austenitic stainless steels
2219	wrought aluminum alloy with Cu as principal alloying element
4130	high-strength martensite-hardening low-alloy steel
5083	wrought aluminum alloy with Mg as principal alloying element
6061	wrought aluminum alloy with Mg and Sn as principal alloying elements

ABBREVIATIONS

Organization	Identification
AFRPL	Air Force Rocket Propulsion Laboratory
AGARD	Advisory Group for Aeronautical Research & Development
AIAA	American Institute of Aeronautics & Astronautics
ARS	American Rocket Society
ASME	American Society of Mechanical Engineers
CPIA	Chemical Propulsion Information Agency

Organization	Identification
ICRPG	Interagency Chemical Rocket Propulsion Group
JANNAF	Joint Army-Navy-NASA-Air Force
JPL	Jet Propulsion Laboratory
NACA	National Advisory Committee for Aeronautics
ORNL	Oak Ridge National Laboratory
SAE	Society of Automotive Engineers
WADC	Wright Air Development Center

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SP-8024	Spacecraft Gravitational Torques, May 1969
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SP-8047	Spacecraft Sun Sensors, June 1970
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SP-8113	Liquid Rocket Engine Combustion Stabilization Devices, November 1974
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SP-8112	Pressurization Systems for Liquid Rockets, October 1975
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